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Estimating aggregation between suspended sediments and frazil ice

Lars H. Smedsrud

Geophysical Institute, University of Bergen, Norway

Abstract. This paper aims to describe the scavenging process, one of the main processes for incorporating sediments (particles) into sea ice. An experiment with suspended sediment and frazil ice in a homogeneous turbulent flow is presented. At the end sediment where incorporated into the surface grease ice. The ice production was constant, and calculated from the salinity measurements, while the turbulent dissipation rate was calculated from high resolution current measurements.

A model for aggregation between suspended sediment and frazil is also presented and used to simulate the experiment. The modelled aggregation process depends primarily on concentrations, on the turbulence levels, and on the (constant) radii of the sediments and ice.

Efficiency of the aggregation process is estimated from the model and experimental results, and the "aggregation" factor is found to be $\alpha \sim 0.025$. This is consistent with theoretical estimates, qualitative observations from laboratory experiments, and field data. Sensitivity analyses suggest that the results does not depend greatly on uncertainty of model parameters.

Introduction

Entrainment of sediments into newly forming Arctic sea ice is important to understand for several reasons: it changes the albedo drastically e.g. [*Ledley and Pfirman*, 1997], ice can become an efficient long-distance carrier of 0 that are bonded to the sediments e.g. [*Pfirman et al.*, 1997], and it contributes to coastal erosion and deep sea sedimentation in ablation areas. Both climate and environmental studies are thereby affected. Numerous field expeditions have mapped the levels of sediments concentrations, having a very large variability, for instance [*Nürnberg et al.*, 1994].

There has been a long running discussion on which process(es) are the most important for sediment incorporation into the Arctic surface ice cover [*Osterkamp and Gosink*, 1984], [*Reimnitz et al.*, 1993], [*Ackermann et al.*, 1994], and whether salt water frazil in super cooled water is "sticky" [*Kempema et al.*, 1993]. An aggregation factor, α, will be estimated from the experiment. Assuming that α stays fairly constant, the model will relate the sediment content of newly formed ice for the scavenging process [*Osterkamp and Gosink*, 1984] to basically five parameters: Sediment concentration, Ice production, the turbulent dissipation rate, and the particle radii of sediment and frazil ice.

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The Experiment

The experiment represent open turbulent water at the freezing point with suspended sediment, and was carried out in a 22 m long, 6 m wide and 1 m deep race track flume. Impellers made a mean current of about 10 cm/s, a wave generator created waves with an amplitude of a few cm, and a wind machine a wind of about 5 m/s above the surface. The experiment was started with a water salinity of about 36 psu, at the freezing point, and ran for 6 hours with a constant air temperature of -15^{o}C.

Turbulence levels within the water column were calculated from Ultrasonic Current Meter data with accuracy ± 5 mm/s for the u,v, and w components, and a frequency of 2 Hz. In situ salinity and water temperature were measured with a CTD with accuracy ± 0.002 for psu and ^{o}C.

Sediments (mostly silts, median radius = 2.5 μm, maximum = 40 μm) were kept in suspension within the water column due to the turbulent current and the waves. The suspended sediment concentration was measured in the beginning of the experiment at the surface, at 0.25 m, 0.5 m, 0.75 m depth, and at the bottom at 1.0 m. Water samples were filtered over preweighted Durapore filters (0.45 μm).

Suspended ice crystals were collected with a 5 l water sampler at depths of 0.1 m, 0.5 m and 1 m at various times. The depth was measured with a meter stick, and the bottle was allowed to stay at that depth 30 s to remove deployment effects. The crystals were retained after sieving through a 63 μm mesh, and were then weighed. The salinity of the melt water was then measured. Because some salt water remained to wet the crystals the mass of pure ice was determined from this. The size of the ice crystals were judged by eye, and from photographs through polarised glass, of samples lifted out of the water in a small glass plate.

At the end of the experiment, when the impellers had been turned off and all the ice had risen to the surface, 5 grease-ice samples were taken to measure the incorporated sediment concentration. These samples were drained and melted before the salinity was measured and they were filtered like the water samples.

Experiment Results

An average total upward heat flux of 125 W/m^2 was calculated from the salt and temperature record for the experiment, which includes cooling of the water and ice production (figure 1). The water was slightly super cooled ($\sim 0.03^o$C) for the entire experiment. Ice concentrations at three depths are also shown in figure 1, showing the vertical homogeneous distribution. The ice production P_i corresponds to a salinity increase of 0.35 psu/hour, which was measured by the CTD until 3.5 hours when the conductivity sensor was blocked by

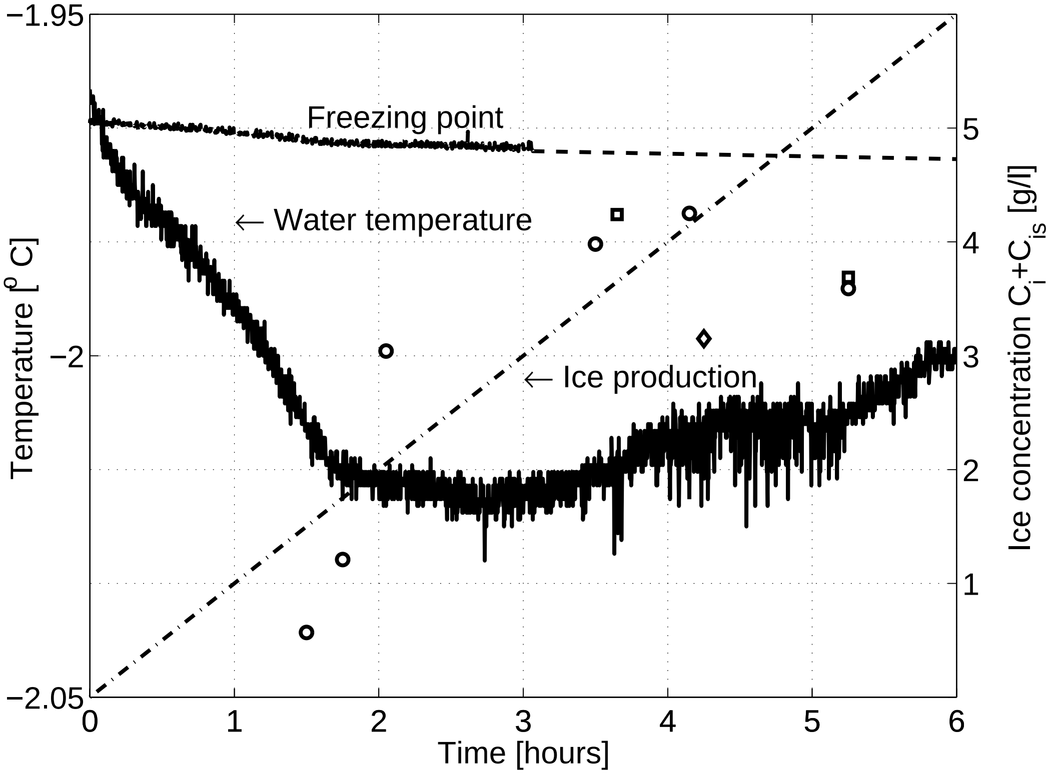

Figure 1. Measured water temperature (–) and ice concentration at 0.1 m (◇), 0.5 m (○), and 1 m (□) depth. The freezing temperature (– –) and the ice production rate $P_i \cdot t$ (– ·) are calculated from the salinity measurements (not shown).

an ice crystal. The radii of the ice crystals was estimated as ~ 1 mm in radius, with a thickness of 0.1 mm.

Determined sediment concentration in the water was 12 mg/l (±1.0) at all depths [*Lindemann*, 1997]. At the end of the experiment the sediment content of the 5 melted grease-ice samples varied between 7.4 and 21.2 mg/l, and the grease ice contained 44 % water on average when drained [*Lindemann*, 1997].

The mean flow had a Reynolds number of ~ 5.0 10^4, and appeared to be isotropic from the energy spectrums of u,v, and w components (not shown). The energy at different frequencies is then given by

$$\Psi = \epsilon^{(2/3)} u_t^{(2/3)} \omega^{(-5/3)}, \qquad (1)$$

where $\Psi(\omega)$ is the energy at a specific angular frequency ω, and u_t is the typical turbulence velocity [*Tennekes and Lumley*, 1972]. Since waves were present, ϵ was calculated by filtering velocities with a butterworth filter with a stop band between 0.6 and 0.8 Hz to exclude Ψ from the wave frequencies. u_t was then taken as the rms value of all three current directions.

As a mean over all frequencies $\epsilon = 2.0 \times 10^{-8}$ W/kg was calculated, and the energy spectra agreed well with the (-5/3) slope predicted in (1). The calculated ϵ did not decrease during the experiment.

The Analytical Model

The model is a box model, and treats the water column as homogeneous. This is often a good approximation in the surface mixed layer of shallow shelf seas with high levels of turbulence. The equations developed here could well be implemented in a vertical or 3D numerical model.

The model consists of four coupled-first order linear differential equations;

$$\begin{aligned}
\frac{dC_i}{dt} &= P_i - \frac{\alpha}{t_T}\frac{3}{4\pi}\frac{(r_s+r_i)^3}{r_s^3}C_i[C_s+C_{si}] \\
&- \frac{\alpha}{t_T}\frac{6}{\pi}C_iC_{is} \qquad (2)\\
\frac{dC_s}{dt} &= -\frac{\alpha}{t_T}\frac{3}{4\pi}\frac{(r_s+r_i)^3}{r_i^3}C_s[C_i+C_{is}] \\
&- \frac{\alpha}{t_T}\frac{6}{\pi}C_sC_{si} \qquad (3)\\
\frac{dC_{is}}{dt} &= \frac{\alpha}{t_T}\frac{3}{4\pi}\frac{(r_s+r_i)^3}{r_s^3}C_i[C_s+C_{si}] \\
&+ \frac{\alpha}{t_T}\frac{6}{\pi}C_{is}C_i \qquad (4)\\
\frac{dC_{si}}{dt} &= \frac{\alpha}{t_T}\frac{3}{4\pi}\frac{(r_s+r_i)^3}{r_i^3}C_s[C_i+C_{is}] \\
&+ \frac{\alpha}{t_T}\frac{6}{\pi}C_{si}C_s \qquad (5)
\end{aligned}$$

where the volume concentrations are (C_i) and (C_s), and the subscript denotes pure ice or sediments, or a mixture. C_{is} is ice with aggregated sediment and C_{si} is sediment with aggregated ice. P_i is the ice production rate per volume of water, α is an "aggregation" factor, and t_T is a turbulent time scale. r_i and r_s are the equivalent radii of the ice crystals, and the sediment grains, respectively. Equation

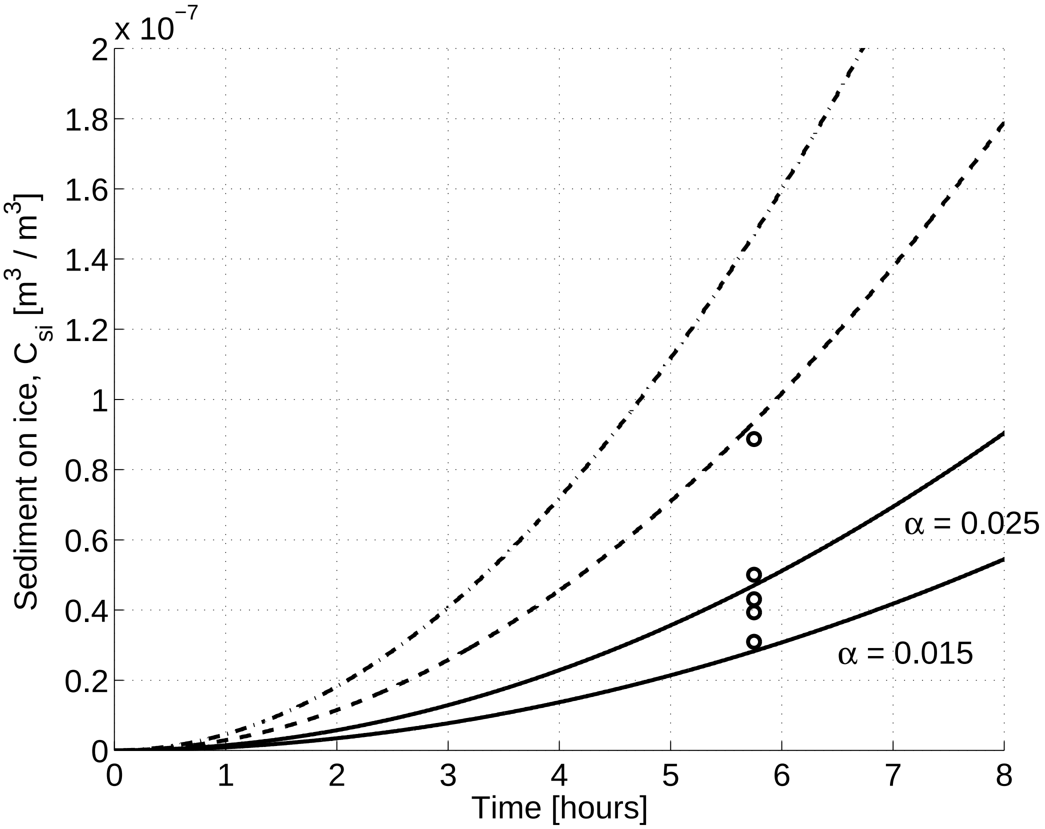

Figure 2. Increasing concentrations of sediment on ice, C_{si}, from model calculations for $\alpha = 0.015$ and $\alpha = 0.025$ (–). The measured sediment content from the experiment is shown as (∘) *[Lindemann, 1997]*. The two upper curves shows the effect of doubling P_i or C_s (– –) , and increasing ϵ with an order of magnitude (– ·) for $\alpha = 0.025$.

(2) - (5) describes the changes in volume concentrations of ice or sediment (volume of sediment or ice per volume of water) due to collision and aggregation between them.

Although frazil crystals have very complex dendritic forms, and a thickness 3-50 times less than their radius [*Daly et al.*, 1994], they are modelled as spheres. r_i is the equivalent radius of a sphere with the same volume as the average crystal. Sediments also have irregular shapes, but are modelled as spheres with r_s as the median radius of the load. The assumptions behind equations (2) - (5) are from classic aggregation theory [*Shamlou*, 1993], and the radius factors arises due to the difference in size of the two particles. The equations were used by [*Eidsvik*, 1997] in a vertical model, but are not tested by measurements. The equations are consistent with the basic ideas of [*Osterkamp and Gosink*, 1984].

Table 1. Sensitivity of estimates for α to crystal radius r_i, sediment-grain radius r_s, and dissipation rate n.

Mode	r_i, μm	r_s, μm	ϵ, W/kg	α
Normal	500	2.5	2×10^{-8}	0.025
Small r_i	50	2.5	2×10^{-8}	0.020
Large r_i	5000	2.5	2×10^{-8}	0.028
Small r_s	500	0.1	2×10^{-8}	0.028
Large r_s	500	40	2×10^{-8}	0.020
Small ϵ	500	2.5	2×10^{-9}	0.070
Large ϵ	500	2.5	2×10^{-7}	0.007

There is only one concentration C_{is} for all ice with attached sediments, even though there will be various clusters of ice crystals and sediment grains with different sizes, shapes, densities and rise velocities. Likewise will C_{si} represent all the different sediment grains on one or more crystals. C_{is} gives an upper limit on how much sediment that can be attached to the ice on average before it sinks due to negative buoyancy, so if $C_{si} > 6\%\ C_{is}$ then anchor ice will form. This did not happen during this experiment. Pure crystal and grain aggregates are treated as if they are all separate in the flow. In reality, ice-ice or sediment-sediment aggregates would have larger radii but a lower number concentration. These changes would have opposing effects on aggregation.

The strength of the turbulence is represented by the Taylor time scale $t_T = (\frac{15\nu}{\epsilon})^{(1/2)}$ [*Tennekes and Lumley*, 1972], where ν is the kinematic viscosity, and ϵ the turbulent dissipation rate. This applies because r_i and r_s are smaller than the Kolmogorov micro scale $(\nu^3/\epsilon)^{1/4}$.

The model can be applied for a limited time only, because the assumptions about the physical system eventually become invalid. At some stage there will be so much ice that it affects the flow characteristics, reducing turbulence and heat exchange. Vertical distributions of ice and sediment will become important, and grease ice will appear on the surface.

Model Calculations

Equations (2) - (5) were solved numerically with a time step of 30 s for an eight hour simulation of the experimental conditions. α is clearly the most uncertain parameter, and was varied to fit the observations. α will have values between 0 (i.e. no aggregation) and and a maximum on the order of one [*Shamlou*, 1993].

The model runs used the following measured parameters: $P_i = 0.3 \times 10^{-6}\ s^{-1}$ (equivalent to 1 g/(l hour)), and $r_i = 500\ \mu$m. The ice concentration C_i is initially zero. Initial $C_s = 4.44 \times 10^{-6}$ (equivalent to 12 mg/l), and $r_s = 2.5\ \mu$m. To convert from measured mass to volume a density of 920 kg/m^3 was used for ice, and 2650 kg/m^3 for sediment. t_T was calculated as 36.74 s, from an $\epsilon = 2.0 \times 10^{-8}$ W/kg and $\nu = 1.8 \times 10^{-6}\ m^2/s$. C_{si} was calculated using $1.8 \cdot [C_i + C_{is}]$ to correct for 44 % water content in the slush ice surface sample. C_{si} at 5.75 hours ranged from 0.27×10^{-7} to 0.78×10^{-7}.

Figure 2 shows the increasing concentration of sediment on the ice (C_{si}) with time, and the five measurements. It was not possible to distinguish between ice crystals which had sediment on them (C_{is}) and which had not (C_i), but $[C_i + C_{is}] \equiv P_i \cdot t$. C_s stayed nearly constant due to the relatively small volumes of ice.

Discussion and Results

Best agreement between observed values of C_{si} and calculations was obtained with $\alpha = 0.025$. This agrees with theoretical estimates [*Osterkamp and Gosink*, 1984], and aggregation coefficients from other multi phase-flows [*Shamlou*, 1993], but is smaller than coefficients for aggregation between different size of ice crystals [*Omstedt*, 1984].

The best-fit value of α is not highly sensitive to variations in r_i, r_s and ϵ, and are tabulated in Table 1. The observed crystal radius was $50\mu < r_i < 5\ mm$. Likewise, the whole sediment distribution was bracketed by the tabulated values of r_s. It is more difficult to put limits on the possible error in the calculations of ϵ, but one order of magnitude is a common value [*Tennekes and Lumley*, 1972]. Because $C_i + C_{is}$ and C_s were determined directly, these results indicate that $0.007 < \alpha < 0.07$, and most likely in the neighbourhood of 0.025.

The model is very stable, and nearly "linear" in its response to changes in ice or sediment concentration (i.e. a doubling of P_i or initial C_s results in a doubling of C_{si} at any given time). This is shown in figure 2 for $\alpha = 0.025$. Increasing ϵ by an order of magnitude to 2.0×10^{-7} W/kg results in a threefold increase in C_{si}. The model has a weak dependency on the radii. It will give higher levels of C_{is} with increasing r_i, and higher levels of C_{si} for increasing r_s. However, if the ratio of r_i/r_s remains constant, nothing will change.

The model calculates sediment aggregated to ice in suspension. To compare with field data from Arctic sea ice, one needs to let the frazil rise and form a solid cover. By applying the standard run for 12 hours, about 2 cm of solid ice crystals are formed, with a mean sediment concentration of 28 mg/l. This gives an enrichment factor above two in comparison with the water concentration of 12 mg/l. This is within observed field values [*Nürnberg et al.*, 1994], and also comparable to earlier qualitative laboratory experiments [*Reimnitz et al.*, 1993], [*Ackermann et al.*, 1994].

It is unfortunate that the possible nonlinear nature of the aggregation process cannot be confirmed by the measurements, and further laboratory experiments are planned to examine the time development of C_{si}.

The model results suggest that the approximate treatment of the particle sizes, and shapes as spheres with a single dominant radius may be sufficient, pending further tests against laboratory data.

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L. H. Smedsrud (e-mail: larsh@gfi.uib.no)

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