Estimating aggregation between suspended sediments and frazil ice

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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 do 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 Pflüger, 1997], ice can become an efficient long-distance carrier of $0$ that are bonded to the sediments e.g. [Pflüger 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, $\alpha$, will be estimated from the experiment. Assuming that $\alpha$ 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.

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°C.

Turbulence levels within the water column were calculated from Ultrasonic Current Meter data with accuracy $\pm 5$ 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 $\pm 0.002$ for psu and °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 pre-weighted 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/m² 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 (~ 0.03°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 \( \sim 1 \text{ mm} \) in radius, with a thickness of 0.1 mm.

Determined sediment concentration in the water was 12 mg/l \( (\pm 1.0) \) at all depths \cite{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 \cite{Lindemann, 1997}.

The mean flow had a Reynolds number of \( \sim 5.0 \times 10^4 \), 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

\[
\Psi = \epsilon^{2/3} u_t^{(2/3)} \omega^{(-5/3)},
\]

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

As a mean over all frequencies \( \epsilon = 2.0 \times 10^{-8} \text{ W/kg} \) was calculated, and the energy spectra agreed well with the \(-5/3\) slope predicted in (1). The calculated \( \epsilon \) 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;

\[
\frac{dC_i}{dt} = \frac{P_i}{t_T} - \frac{\alpha}{t_T \cdot 4\pi} \frac{(r_s + r_i)^3}{r_i^3} C_i C_s + C_{is} \\
- \frac{\alpha}{t_T \cdot 4\pi} C_i C_{is} \tag{2}
\]

\[
\frac{dC_s}{dt} = \frac{\alpha}{t_T \cdot 4\pi} \frac{(r_s + r_i)^3}{r_s^3} C_s [C_i + C_{is}] \\
- \frac{\alpha}{t_T \cdot 4\pi} C_s C_{is} \tag{3}
\]

\[
\frac{dC_{is}}{dt} = \frac{\alpha}{t_T \cdot 4\pi} \frac{(r_s + r_i)^3}{r_s^3} C_{is} [C_i + C_{is}] \\
+ \frac{\alpha}{t_T \cdot 4\pi} C_s C_{is} \tag{4}
\]

\[
\frac{dC_{si}}{dt} = \frac{\alpha}{t_T \cdot 4\pi} \frac{(r_s + r_i)^3}{r_i^3} C_{si} [C_i + C_{is}] \\
+ \frac{\alpha}{t_T \cdot 4\pi} C_s C_{si} \tag{5}
\]

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, \( \alpha \) 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
(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].

There is only one concentration $C_s$ 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. $C_s$ 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 $C_{si} > 6\% C_s$ 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 $t_T = (2\nu/\epsilon)^{1/2}$ [Tennekes and Lumley, 1972], where $\nu$ is the kinematic viscosity, and $\epsilon$ 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.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$r_i, \mu m$</th>
<th>$r_s, \mu m$</th>
<th>$\epsilon, W/kg$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>500</td>
<td>2.5</td>
<td>$2 \times 10^{-8}$</td>
<td>0.025</td>
</tr>
<tr>
<td>Small $r_i$</td>
<td>50</td>
<td>2.5</td>
<td>$2 \times 10^{-8}$</td>
<td>0.020</td>
</tr>
<tr>
<td>Large $r_i$</td>
<td>5000</td>
<td>2.5</td>
<td>$2 \times 10^{-8}$</td>
<td>0.028</td>
</tr>
<tr>
<td>Small $r_s$</td>
<td>500</td>
<td>0.1</td>
<td>$2 \times 10^{-8}$</td>
<td>0.028</td>
</tr>
<tr>
<td>Large $r_s$</td>
<td>500</td>
<td>40</td>
<td>$2 \times 10^{-8}$</td>
<td>0.020</td>
</tr>
<tr>
<td>Small $\epsilon$</td>
<td>500</td>
<td>2.5</td>
<td>$2 \times 10^{-9}$</td>
<td>0.070</td>
</tr>
<tr>
<td>Large $\epsilon$</td>
<td>500</td>
<td>2.5</td>
<td>$2 \times 10^{-7}$</td>
<td>0.007</td>
</tr>
</tbody>
</table>
Model Calculations

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

The model runs used the following measured parameters: $P_i = 0.3 \times 10^{-6} \text{ s}^{-1}$ (equivalent to 1 g/(l hour)), and $r_i = 500 \mu m$. The ice concentration $C_i$ is initially zero. Initial $C_i + C_{si}$ was bracketed by the tabulated values $C_i + C_{si}$ and also comparable to earlier qualitative laboratory experiments [Shamlou, 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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References


