Ice formation in supercooled turbulent water
A parametric study

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Frazil ice and grease ice

- Ice production in polar seas usually takes place in the presence of strong winds.
- In the initial stage, small "frazil" ice crystals are generated at the water surface, where they accumulate to form a slurry of greasy apperance: the so called grease ice.
- Only later does grease ice thicken enough to form more compact objects and hence a continuous solid layer.

Picture of grease ice cover in the Northern Barents Sea.

- Frazil ice formation is a violent process and is responsible of strong increase of heat exchange between the ocean and the atmosphere.

Processes involved in the formation of frazil ice.

- Ice seeds are continuously generated at the water surface (first nucleation), and grow to mm size in the presence of strong overcooling.
- Additional seeds are generated by breaking of crystals from mutual collisions in the grease ice layers (secondary nucleation).
- Part of the crystals get transported down the column by turbulence; another portion may be blown away by the wind; the rest accumulates in the form of grease ice.

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“Complicated” problem with many effects under poor control:

- The growth of the crystals in a complex environment is very difficult to model.
- It is difficult to estimate entrainment of frazil crystals in the underwater turbulence.

What do we know

- Ice grows in overcooled condition: $T - T_i < 0$.
- The freezing temperarature decreases with salinity, $T_i = T_{iB} - a_S S$ (S is the increase of salinity with respect to the background S_B).
- Latent heat $\mathcal{L}$ is released in the liquid phase during freezing.
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We can estimate how much ice forms in thermoisolated conditions from an initial overcooled state (T_0, S_0).

- Water gets warmer and saltier. Imposing $T - T_i = 0$ allows us to get the ice fraction at saturation

$$C = (\rho_w/\rho_i)(a_S S_B + \mathcal{L}/c_P)(T_{i0} - T_0).$$

- It can be seen that the effect of the increase of T dominates over that of S during the process.
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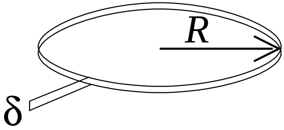
Is it big or is it small?

Volume fraction of grease ice

Typical geometry of frazil crystal

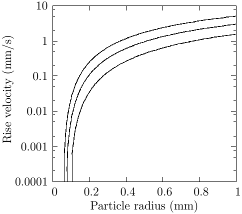


Sketch of a frazil crystal

- Radius of ripe crystal $R \approx 1\,\text{mm}$, $\delta/R \approx 0.01$.
- Effective volume of the crystal $\approx R^3$.
- Volume fraction occupied by ice $\approx \delta/R$.

- This leads us to expect $C_{grease} \approx \delta/R \approx 0.01$.
- A mixture with smaller crystals would lead to a mortar-like, more compact assembly with higher C.
- Transport processes are obviously important (you need them to get $C \approx C_{grease}$).

Rise velocity of the frazil crystals



Plot of frazil crystal rise velocity for different aspect ratios. From bottom to top, $\delta/R = 1/100,\ 1/50,\ 1/25$.

We are in a forced turbulence situation, induced by strong wind at the water surface ($u^{wind} \approx 10\,\mathrm{m/s}$, leading to a friction velocity $u_* \approx 3\,\mathrm{cm/s}$ underwater). In the first approximation we can disregard the rise velocity of the crystals.

Turbulence structure

Navier-Stokes dynamics (Boussinesq)

$$(\partial_t + \mathbf{u}\cdot\nabla)\mathbf{u} + \frac{1}{\rho_w}\nabla P = \nu\nabla^2\mathbf{u} - \hat{\alpha}_T T + \hat{\alpha}_S S - \hat{\alpha}_C C,$$

$$\hat{\alpha}_T \simeq 3.79\cdot 10^{-4}\ \mathrm{m/(^oC\,s^2)};\quad \hat{\alpha}_S \simeq 7.7\cdot 10^{-3}\ \mathrm{m/(psu\,s^2)};$$

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- We can estimate the contribution to buoyancy from an increase δC in the ice volume fraction:

$$\delta T \sim \frac{\rho_i \mathcal{L}}{\rho_w c_P}\delta C \quad \text{and} \quad \delta S \sim \frac{\rho_i S_B}{\rho_w}\delta C, \quad \text{leading to}$$

$$\frac{\hat{\alpha}_T \delta T}{\hat{\alpha}_C \delta C} \simeq 0.06 \quad \text{and} \quad \frac{\hat{\alpha}_S \delta S}{\hat{\alpha}_C \delta C} \simeq 0.24.$$

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- Ice dominates salinity, which dominates temperature.

The mechanical turbulence layer

- The Obukhov depth L can be determined from the heat flux Φ_T at the surface. Estimates during ice formation range from $2.5 \cdot 10^{-5}\,^{\mathrm{o}}\mathrm{C\,m/s}$ to $2.5 \cdot 10^{-4}\,^{\mathrm{o}}\mathrm{C\,m/s}$. What we get depends on how much ice forms at the surface.

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- If all the ice were transported down the column, L would be further reduced, with possibility of a double convection regime at $z < -L$.

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- Simple parametrization of ice production:

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- Two limit scenarios, depending on ice entrainment at the surface:
  - Little ice transported down the column. All ice melts at $z < -L_o$. Little effect on T_o.
  - Lots of ice transported down the column. $T_o \to 0$, with little effect on C. Ice reaches bottom of mechanical turbulent layer.

Latent heat vs sensible heat fluxes

- A situation in which lots of ice get transported down the column is observed in LES (Matsumura & Ohshima, Ann. Glaciol. 2015) as well as in older 1D models (Omstedt and Svensson, J. Geophys. Res. 1984).
- Condition for ice production to dominate overcooling down in the column (assuming stationarity): $T_o^* \ll \hat{\mathcal{L}} C_*$, which implies

  sensible heat flux $\ll$ **latent heat flux from ice transport**.

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- The sensible heat flux, however, cannot be zero.

Estimate of the sensible heat flux

- We can decompose the temperature and salinity fields T and S in an overcooling component $T_o = T - T_{iB} + a_S S$ and a neutral component $T_n = T - T_{iB} - cS$, $c = \hat{\mathcal{L}}/S_B$, which is purely advected with no influence to and from ice formation.
- From here, we can express the heat and salinity fluxes as

$$\Phi_T = \Phi_{T_o} + (a_S/c)\Phi_{T_n} \quad \text{and} \quad \Phi_S = \frac{\Phi_{T_o} - \Phi_{T_n}}{a_S + c},$$

  where Φ_{T_n} is conserved.
- $\Phi_T(0)$ contains both latent and sensible heat fluxes; from $\Phi_S(0) = 0$, we get $\Phi_T(0) = (1 + a_S/c)\Phi_{T_n}$.
- At sufficient depth, $\Phi_T = \Phi_T^{sensible} > (a_S/c)\Phi_{T_n}$ (fluxes positive defined upwards).
- This gives

$$\frac{\Phi_T^{sensible}}{\Phi_T^{latent}} > \frac{a_S}{c - a_S} \simeq 0.1.$$

Conclusions

- Qualitative description of processes taking place in the turbulent column during ice formation.
- Identification of a set of key aspects to further investigate to obtain a proper physical description of what is going on:
  - Entrainment rate of ice crystals on top of the column.
  - Evaluation of the effective diffusivity in the grease ice layer.
  - Evaluation of the ice formation rate within the grease ice layer.
  - Investigation, possibly with LES, of the ice dynamics at and below the Obukhov depth.