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modeling small scale processes in the ocean

Lagrangian frazil ice simulation using a Particle-in-Cell type ocean model

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Arctic Challenge for Sustainability

HPCI High Performance Computing Infrastructure

ILTS

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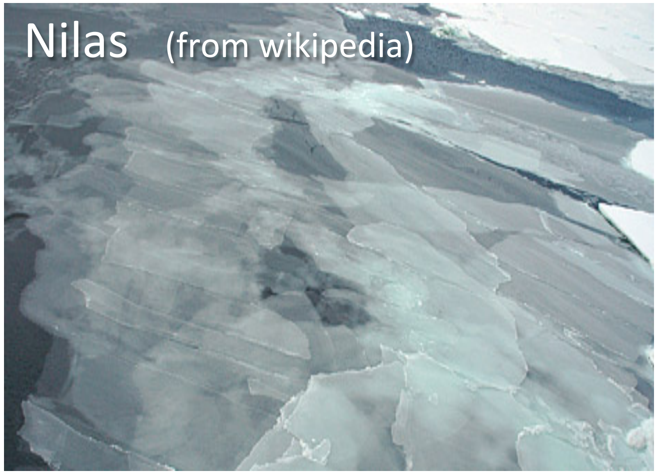
Introduction

Sea ice cover controls atmosphere-ocean heat exchange

Solid Ice cover has very low thermal conductivity (**insulating effect**)
→ Reduce upward heat flux → Restrict new ice formation

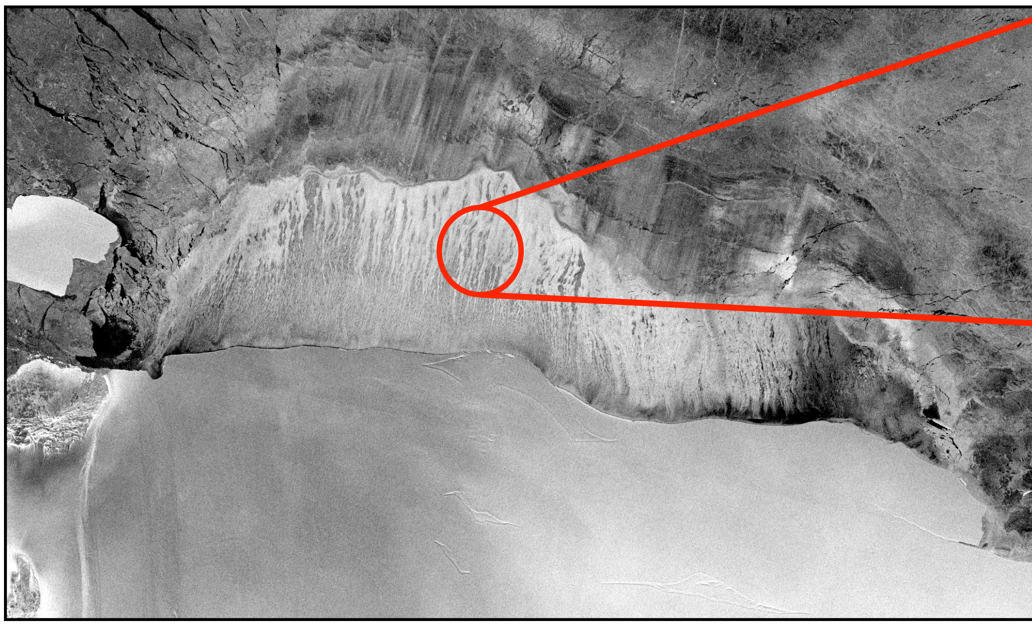
However, the state of newly formed sea ice highly depends on the condition of the ocean surface.

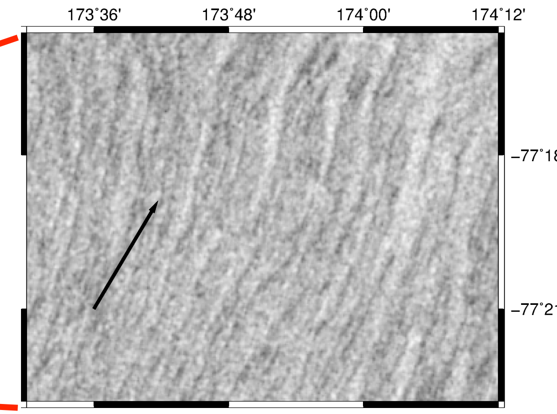


Turbulent sea surface condition forms **grease ice**, mixture of sea ice and small frazil crystals, which has less insulate effect because seawater is directly exposed to the cold atmosphere even after freezing begins.

Introduction

Sea ice cover controls atmosphere-ocean heat exchange





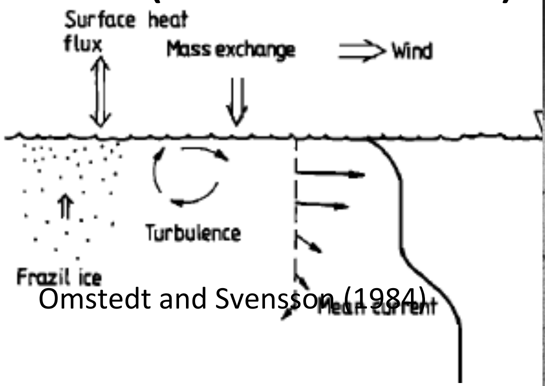
Grease ice cover is typically characterized by the **streak-structure** in satellite images when coastal polynyas develops

Sea ice models widely used in OGCMs/CGCMs can not explicitly deal with such difference of the sea ice state ,
Uncertainty in air-sea heat flux estimation,
particularly in the period of active new ice formation

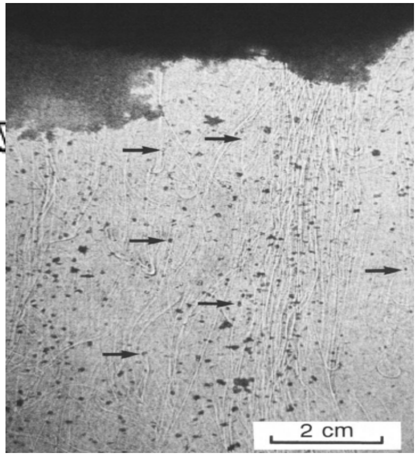
Frazil crystals in supercooled seawater

Surface heat loss → ocean surface is supercooled (~0.01K)
→ fine frazil crystals precipitated → accumulate near the surface
if strong wind: grease ice (granular ice)
otherwise: solid ice (columnar ice)

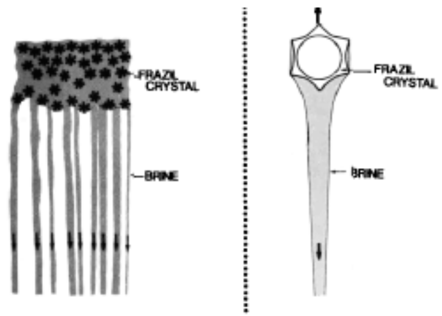
- Drucker and Martine (2003):
  Direct observation of supercooling and frazil at 20m depth by upward sonar
- Smedsrud (2001)
  Laboratory experiments,
  Frazil crystals of up to 2cm diameter
- Ushio and Wakatsuchi (1993):
  Laboratory experiments,
  Visualize Frazil crystal, 0.2K supercooling.
- Bauer and Martine (1983):
  Laboratory experiments,
  consolidation and transformation to grease ice.

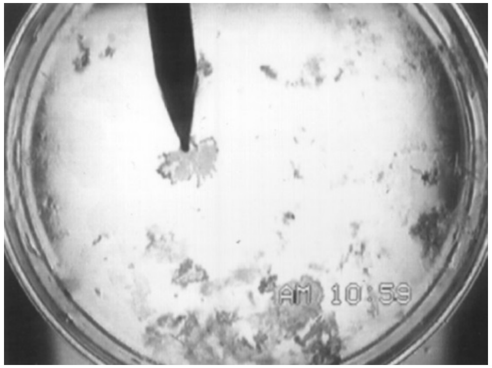


Omstedt and Svensson (1984)



Ushio and Wakatsuchi (1993)





Smedsrud (2001)

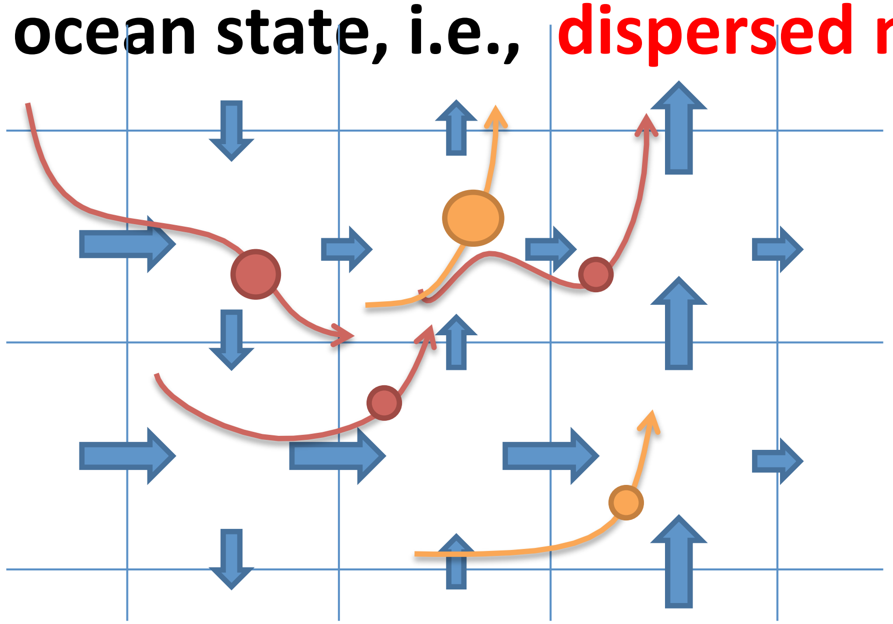
Goal of the present study

- Sea ice component in GCMs does not explicitly deal with grease ice
  → large uncertainty in the period of new ice formation
- Previous modeling studies of frazil ice only deal with **grid-averaged quantity, assume constant crystal size**
- Explicit simulation of **frazil generation and their transition to grease ice** has not been performed yet.
- **Develop a new modeling framework for ice-ocean coupled system which deal with dynamic and thermodynamic effects of underwater frazil ice by using online Lagrangian particle tracking**
- Perform an Idealized experiment of active ice formation at polynyas in the coldest periods.
  → **Quantitatively estimate the effect of frazil ice/grease ice on the atmosphere-ocean heat exchange and net sea ice production.**

"*On-line*" Lagrangian Particle tracking

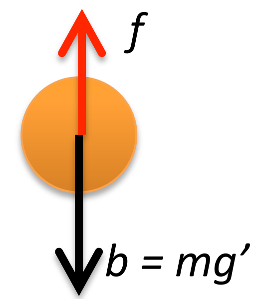
- Trace the location and properties (mass, rise/fall velocity etc.) of each particle (dispersive phase) **simultaneously** with the ocean model (continuous phase), Particle-in-Cell (PIC) type simulation
- Each particle has unique ID and we can trace their history.

→ **Particles can dynamically and thermodynamically affects on the ocean state, i.e., dispersed multi-phase flow**



We developed a numerically efficient particle tracking system built-in a 3D non-hydrostatic ocean model

Dynamic coupling of ocean flow and dispersed particles



- Each particles subject to gravity (body force) and pressure-gradient (surface force)
- Buoyancy: difference between gravity and the hydrostatic pressure gradient

$$b = -mg + \rho_0 \delta g = -m \frac{\rho_s - \rho_0}{\rho_s} g$$

- Residual of pressure gradient: the form drug

$$f \approx -S \rho_0 C_D |v - U|(v - U)$$

Cd: depends on the shape and orientation, UNKONWN

- Water phase feels sum of the reaction of drug force acts on each particle

The question is, how to estimate *f* (or Cd)?

- We assume all particles are in equilibrium state with terminal fall/rise velocity relative to the ocean flow s.t. buoyancy and drug-force is balanced,

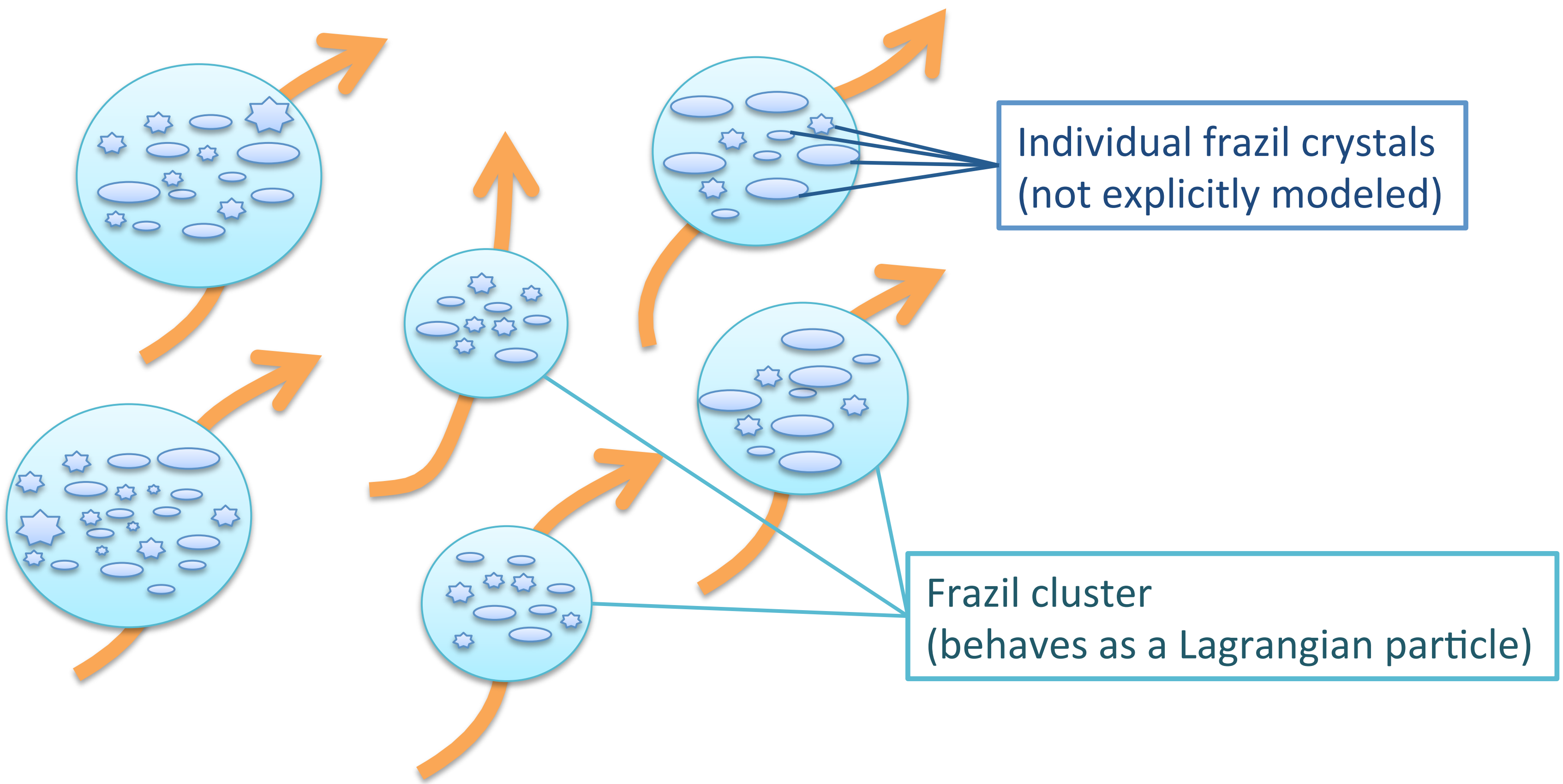
$$f = -b$$ (valid if particles are so small that inertia can be ignored)

$$\rightarrow \frac{dw}{dt} = -g - \frac{1}{\rho_0}\frac{\partial p}{\partial z} - \frac{1}{\rho_0}\sum_i f_i$$
$$= -g - \frac{1}{\rho_0}\frac{\partial p}{\partial z} - \frac{1}{\rho_0 \Delta V}\sum_i m_i \frac{\rho_s - \rho_0}{\rho_s} g = -\frac{\rho^*}{\rho_0} g - \frac{1}{\rho_0}\frac{\partial p}{\partial z}$$

Dynamic effects of suspended particles yields the change of effective water density ρ^*

Modeled frazil particles

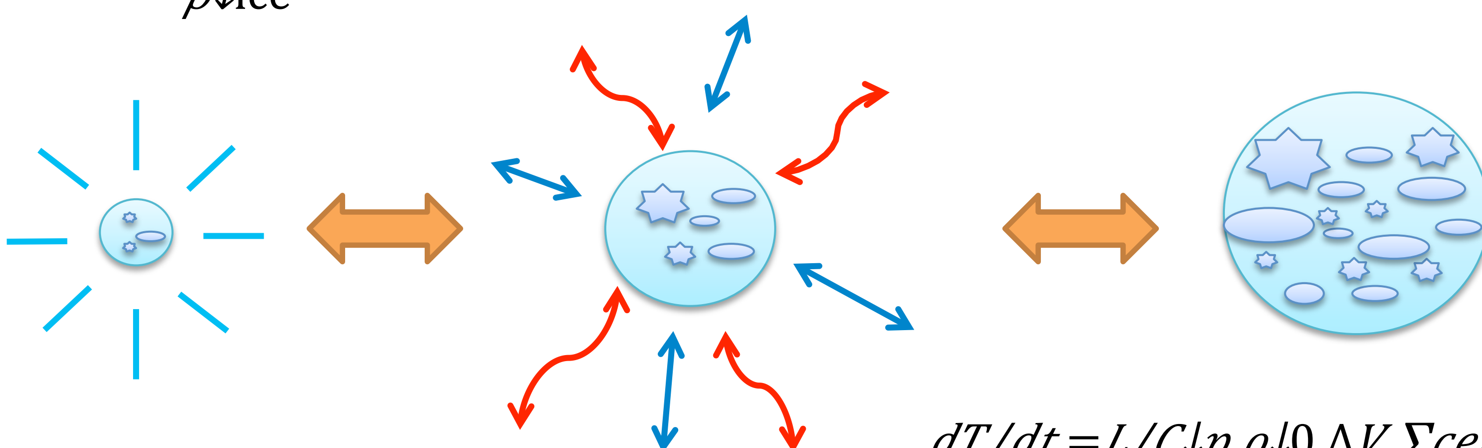
- The actual number of frazil crystals in the real ocean is countless, **impossible to simulate all of them**
  - Modeled particle as **a cluster/packet of many frazil crystals**
  - **Total ice mass** and **average size** of crystals are simulated for each particles.



Thermodynamics

- Generate frazil particles of the minimum mass when the prognostic in-situ temperature falls below the local freezing point
  (sustainable in-situ supercooling state is not allowed)
- Each particle thermodynamically grows/decays depending on the in-situ temperature **relative to the local freezing point *Tf(S, p)***
- The rate of heat exchange depends on the mean crystal size

$$\frac{d}{dt} M_{frazil} = \frac{(T_{freeze} - T_{insitu}) C_p \rho}{L} \frac{\gamma 2 M_{frazil}}{r \rho_{ice}}$$



$$\frac{dT}{dt} = \frac{L}{C_p \rho_0 \Delta V} \sum_{cell} \frac{d}{dt} M$$

Latent heat absorption/emission

Brine rejection/fresh water supply

$$\frac{dS}{dt} = \frac{S_0 - S_i}{\rho_0 \Delta V} \sum_{cell} \frac{d}{dt}$$

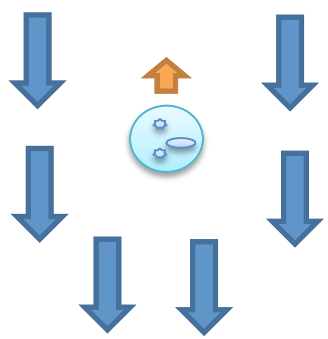
Buoyant rise velocity

- Inertia of frazil crystal are ignored, i.e., all crystals are in equilibrium with terminal buoyant rise velocity
- In the present model individual crystal is not simulated, **just parameterized by using total ice mass of each cluster**.

$$w_{rise} = w_0 \, M_{frazil} / M_0$$, where w_0 = 1mm/s

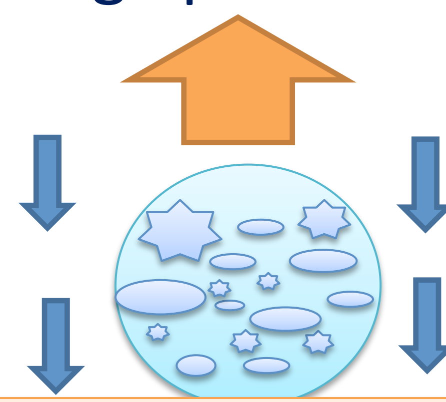
(from Omstedt and Svensson, 1984)

Small particles:



less buoyant force
→ advected by convection

Large particles:



greater buoyant force
→ float up to the surface

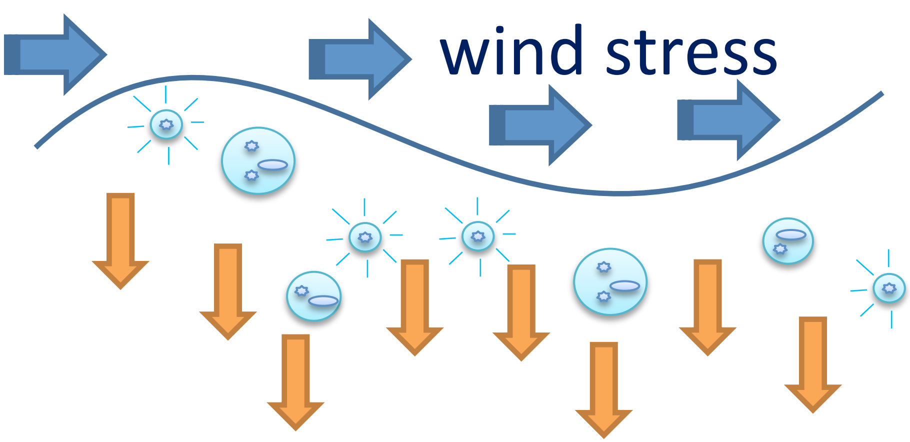
Turbulent mixing by wind stirring

- Net vertical transport of frazil particles is realized by
  Linear interpolation of the predicted ocean current
  \+ buoyant rise velocity w_{rise}
  \+ Subgrid-scale turbulent eddy transport w_{eddy}
- Downward frazil transport increase potential energy, require energy source: Surface wind stress forcing → SGS EKE (or TKE)

$$\epsilon = 2\nu S_{ij} S_{ij}, \quad S_{ij} = 1/2 \left(\partial u_j / \partial x_i + \partial u_i / \partial x_j \right)$$

- The ratio of energy dissipation used to the turbulent eddy transport
  "Critical Flux Richardson Number": $R_f = \sum mg' w / \Delta V \rho_0 \epsilon \approx 0.15$

efficiency of TKE → PE conversion
(from Osborn 1980)



Strong surface wind forcing
→ downward turbulent transport

Enhanced viscosity of slurry

- Grease ice: viscous mixture of frazil crystals and sea water
  - dynamical effects is represented by enhanced viscosity as a function of solid mass fraction

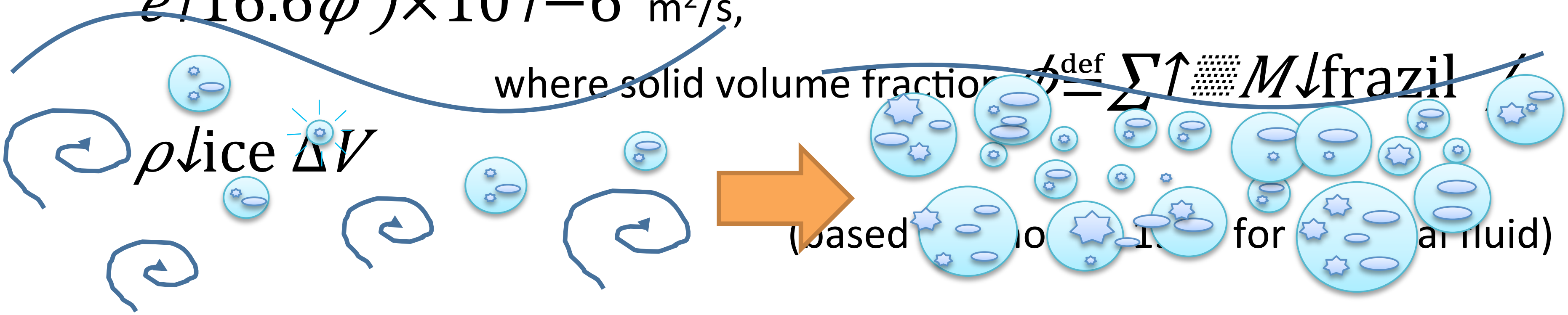
    $$\nu^{*} = \nu_{eddy} + \nu_{mol},$$

  - Sub-grid turbulence model: Smagorinsky-type LES, $\nu_{eddy} = (C_{\mathrm{smag}}\Delta)^{2}|S|$
  - Molecular viscosity is enhanced as a function of solid mass fraction of ice

    $$\nu_{mol} = (1 + 2.5\phi + 10.5\phi^{2} + 2.73\times10^{-3} e^{16.6\phi})\times10^{-6}\ \mathrm{m^2/s},$$

    where solid volume fraction $\phi \stackrel{\mathrm{def}}{=} \sum M_{\mathrm{frazil}} / \rho_{\mathrm{ice}}\Delta V$

    (based … for … fluid)



Large crystals tend to float up to the surface → viscous grease ice cover

Insulating effect of surface ice cover

- Increased solid mass fraction at the surface results in insulating effect
- Net heat flux is parameterized by the effective ice thickness:

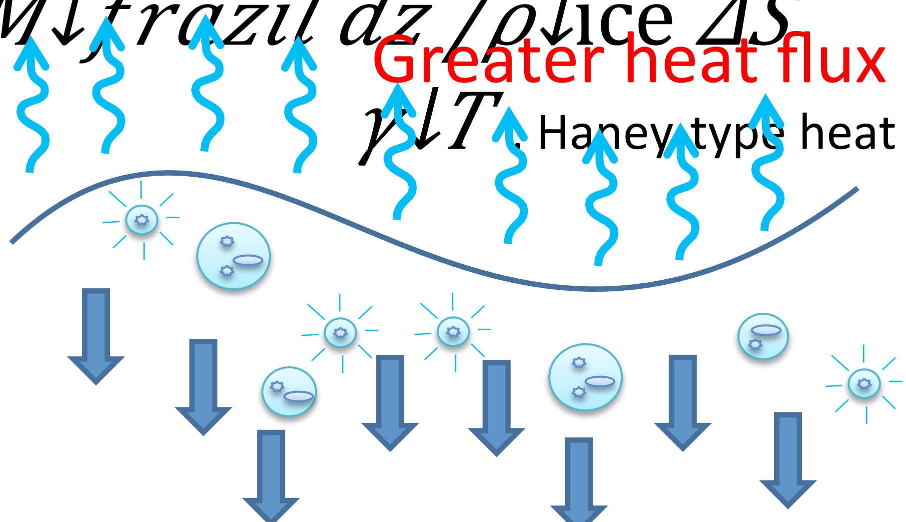
$$Q = -\gamma_T \kappa_{ice} / (\gamma_T h_{ice}^{*} + \kappa_{ice}) (T_{air} - T_{surface}),$$

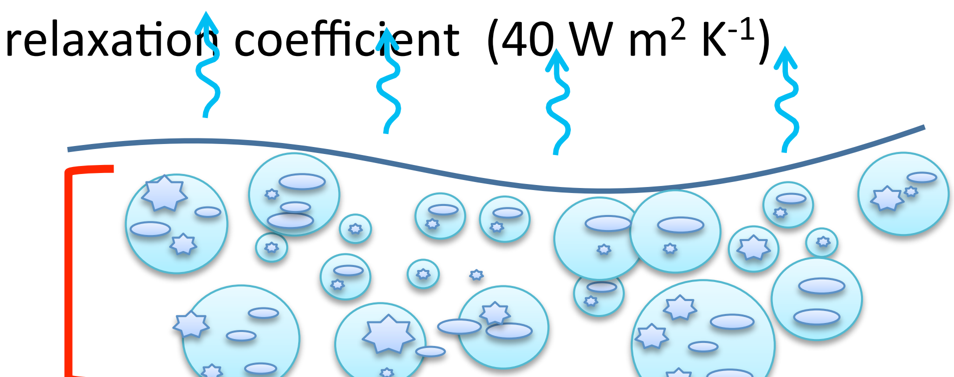
where effective ice thickness $h_{ice}^{*} \stackrel{\text{def}}{=} \int_{z} \exp(-z/\delta) M_{frazil}\, dz / \rho_{ice} \Delta S$

Greater heat flux

Less heat flux

γ_T: Haney type heat relaxation coefficient (40 $W\ m^2\ K^{-1}$)





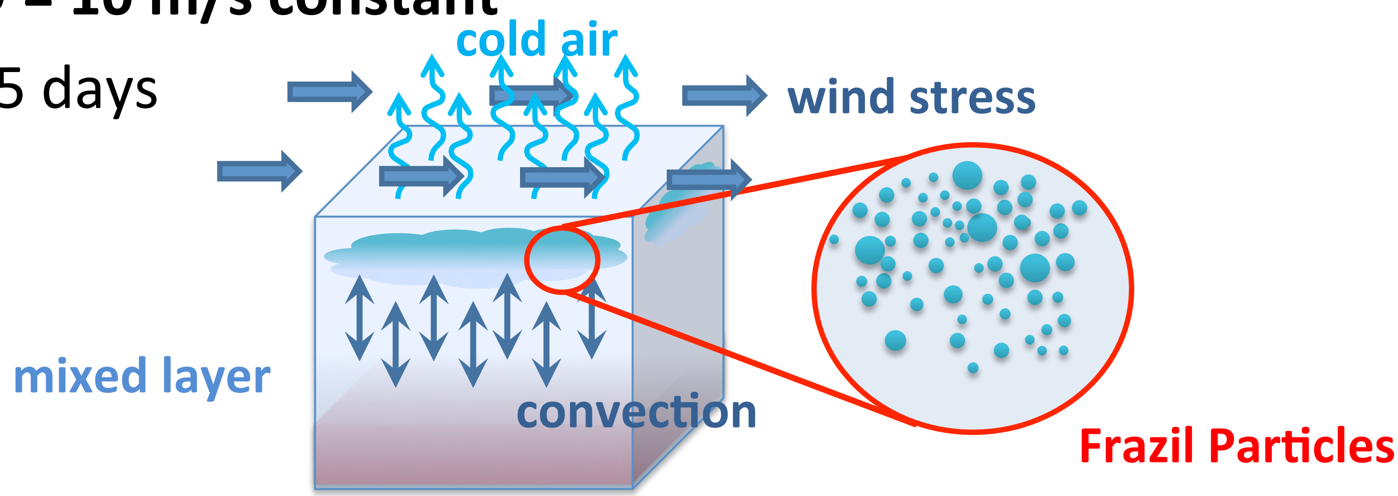
Grease ice layer ~O(10 cm)

Active thermal convection

Frazil generation

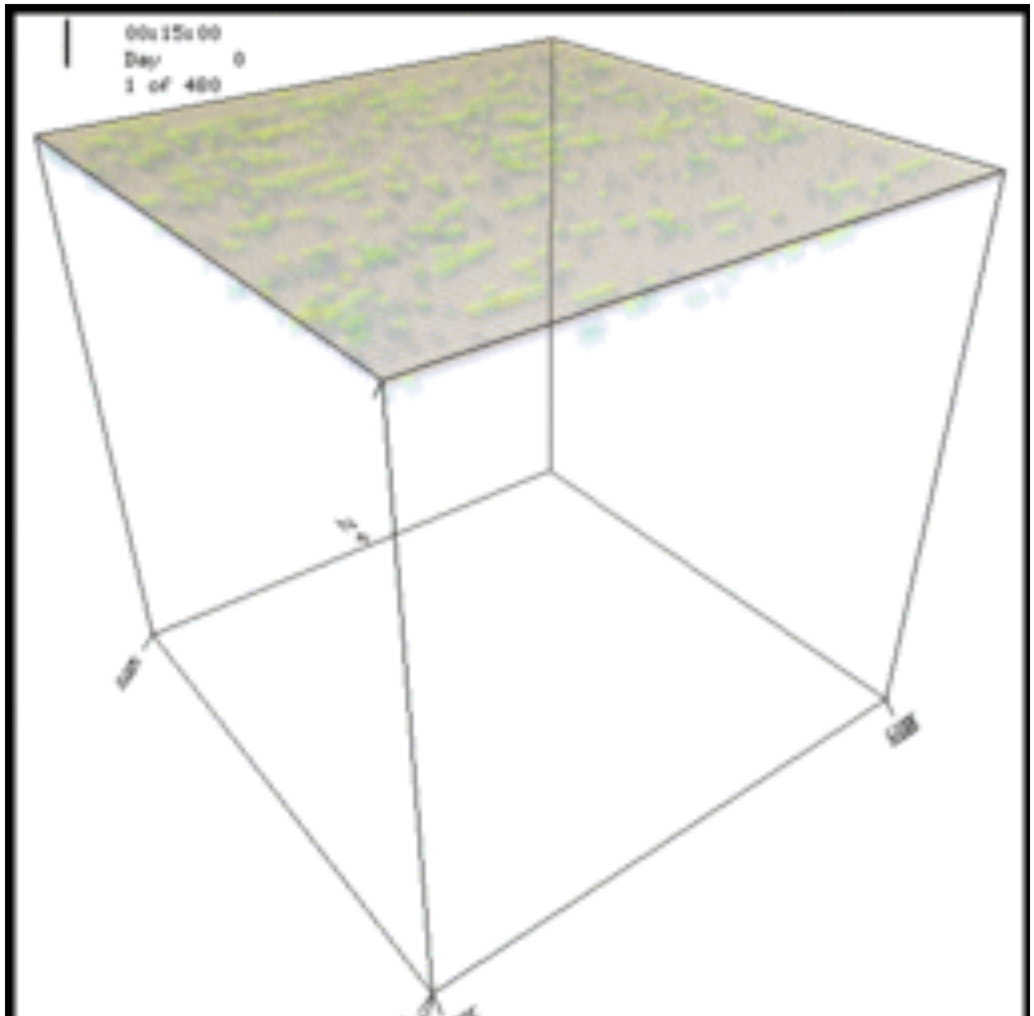
A simple idealized experiment

- Ocean component: kinaco (nonhydrostatic, Matsumura and Hasumi, 2008)
  + Lagrangian frazil ice component (developed in the present study)
- Domain: 64m x 64m x 64m, horizontally periodic boundaries.
- Resolution: 1m x 1m x 1m
- Subgrid-model: Smagorinsky-type shear-dependent LES +
  molecular viscosity enhancement as a function of solid volume fraction
- Initial condition: Θ = -1.6℃, S = 30psu uniform
- Air temperature: **-20℃** (Up to **~730 W/m²** heat flux at the open water)
- Wind forcing: ***U* = 10 m/s constant**
- Integration for 5 days

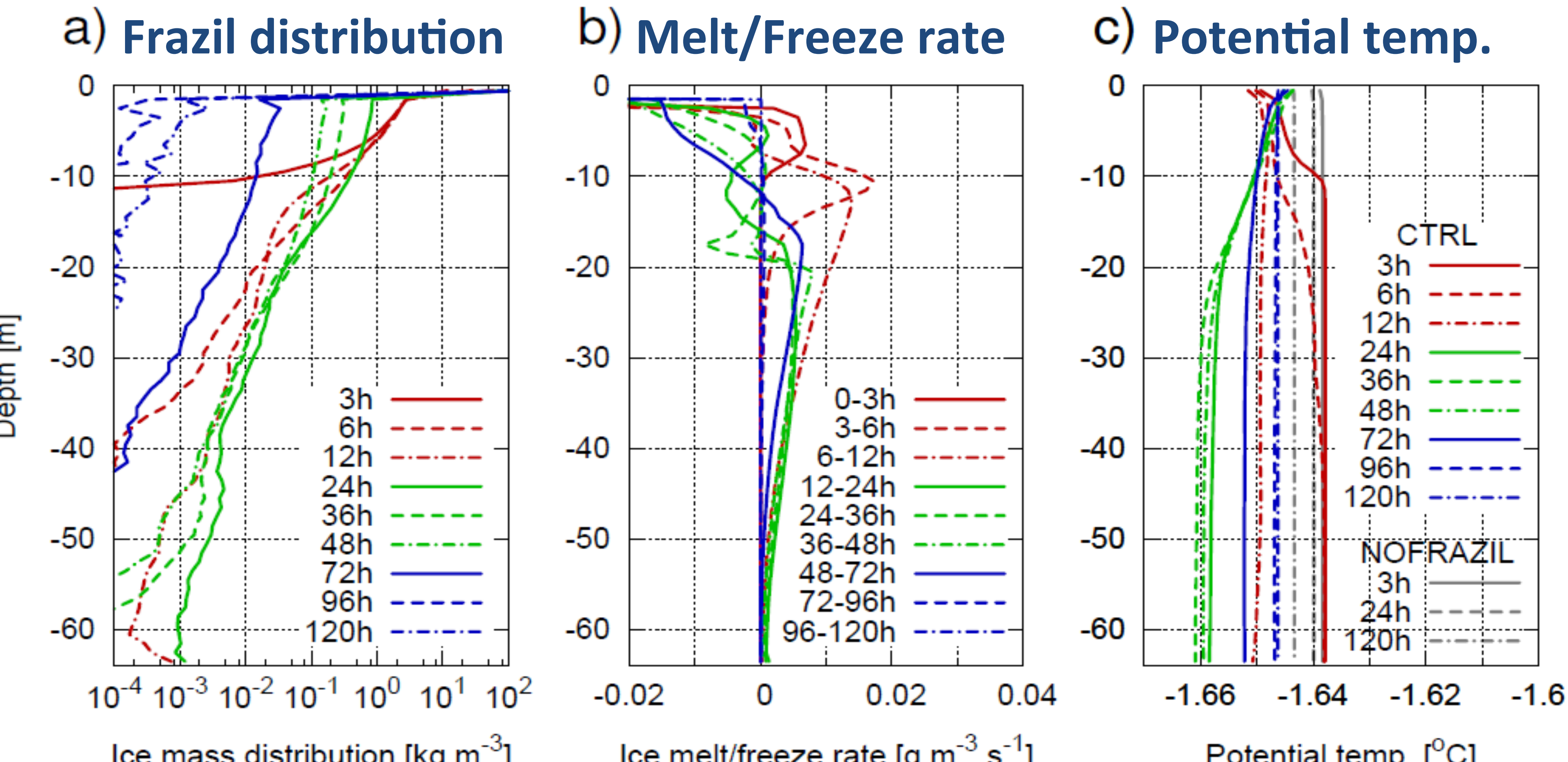


Results

Frazil distribution (log scale, blue 10^{-2} kg/m^3 -- red 10^2 kg/m^3)



Vertical profiles

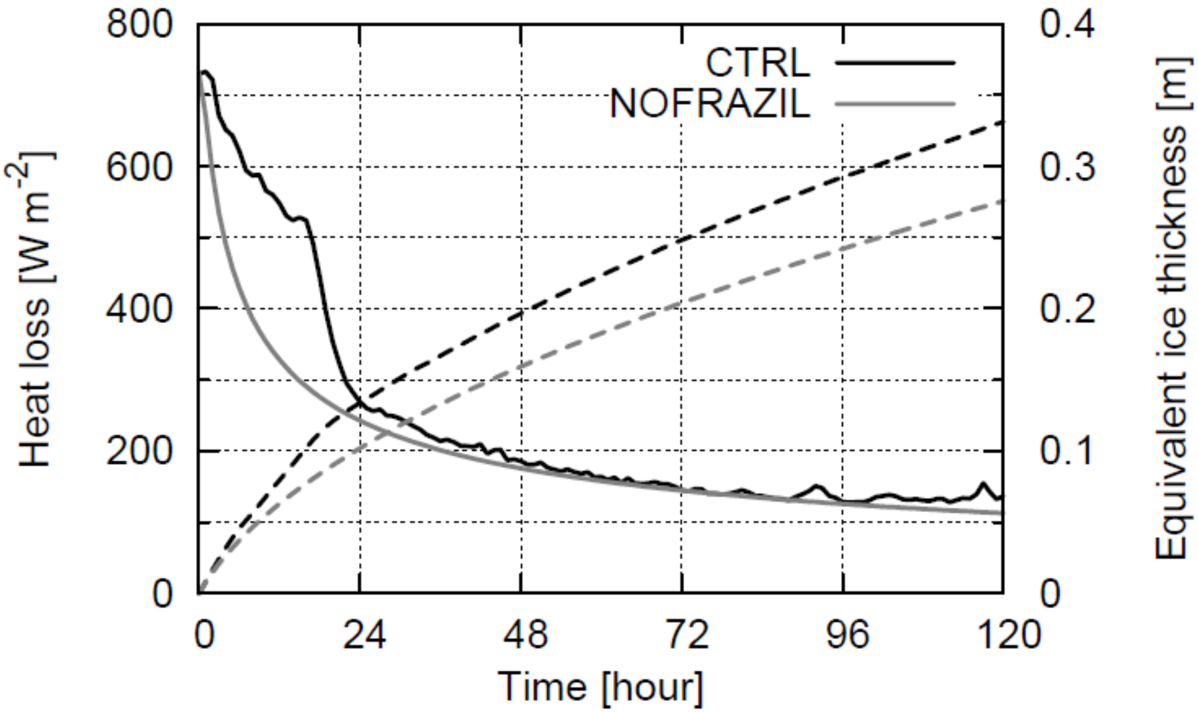


Frazils generated at surface → transported downward by convection → melt at deeper level (absorb latent heat) → cool the water column

→ potential supercooling due to freezing point decline with depth

Surface heat flux and net ice production rate

Compare with the **"0-layer" solid ice thermodynamics**



Newly developed Lagrangian frazil ice model **keeps open water (high heat flux > 500W/m2) relatively longer periods** than 0-layer solid ice

41% greater total heat loss and

34% greater total ice production in the initial 24 hours

both cases become almost equal after the surface is entirely covered

Idealized coastal polynya experiment

→ wind (10m/s)

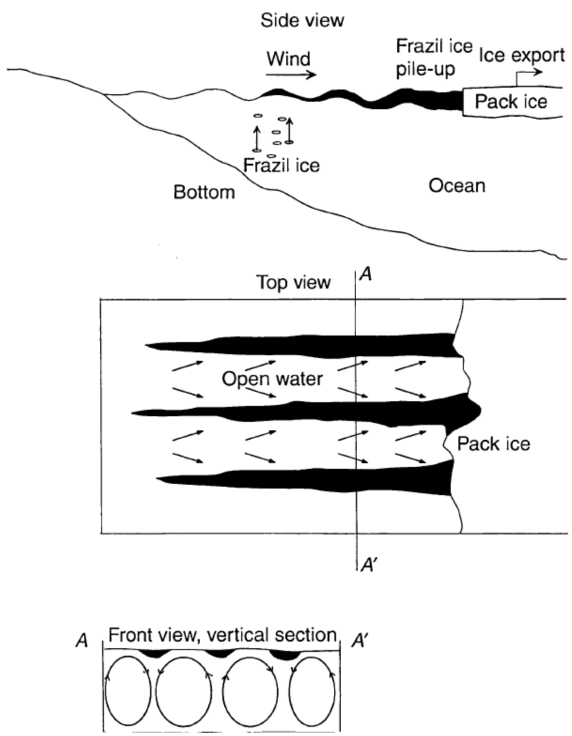
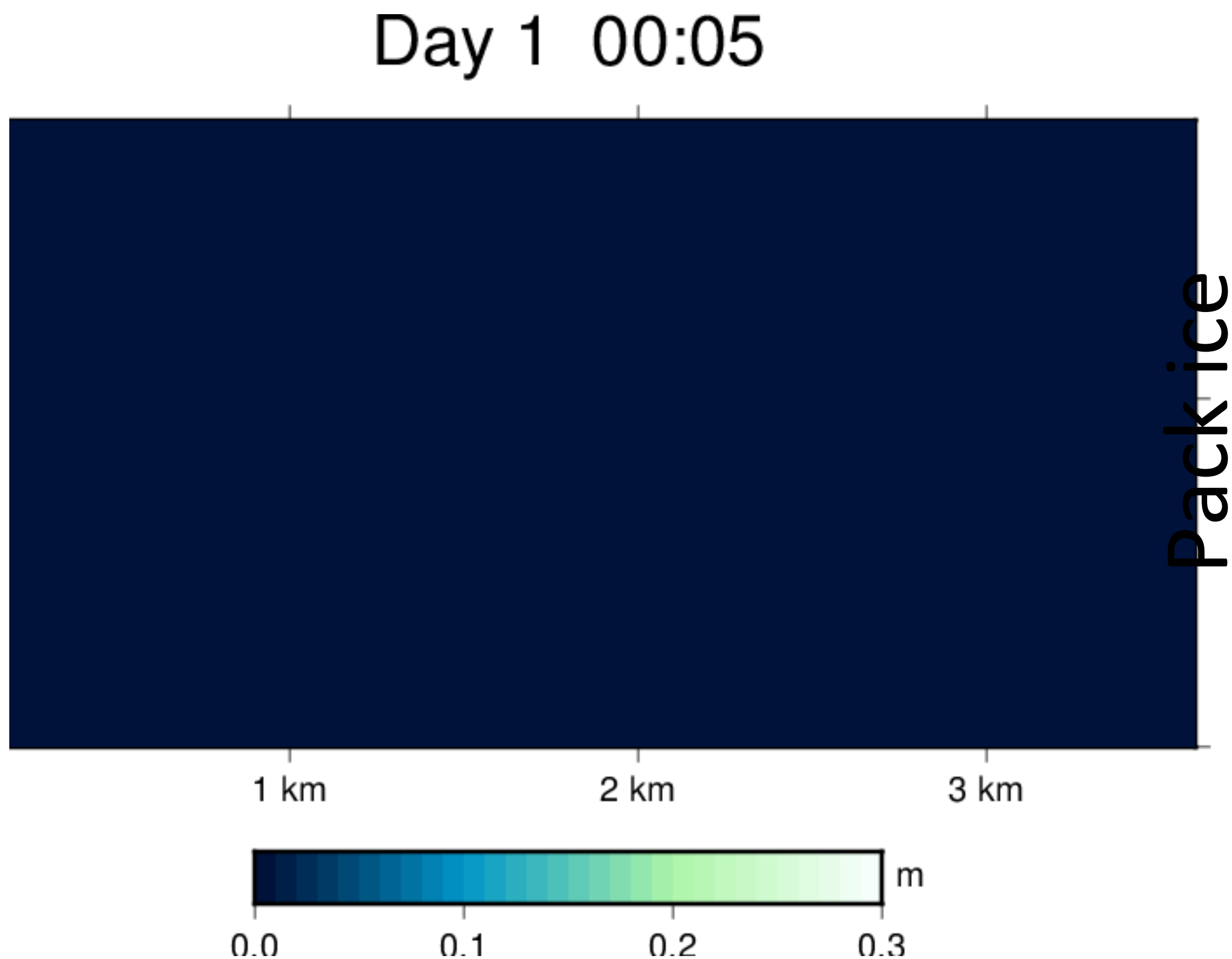
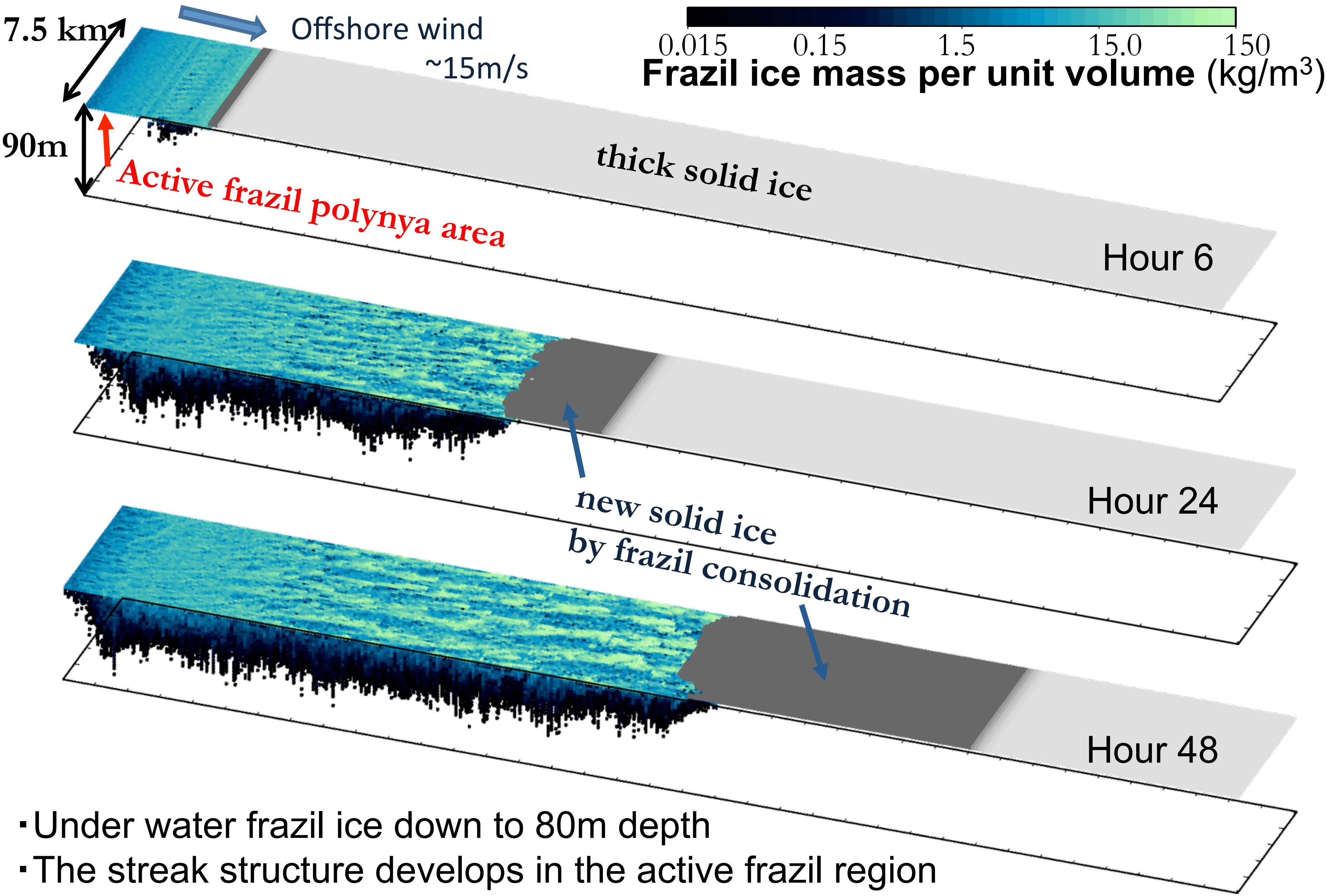


Figure 2 A schematic drawing of a coastal polynya and top and vertical views.

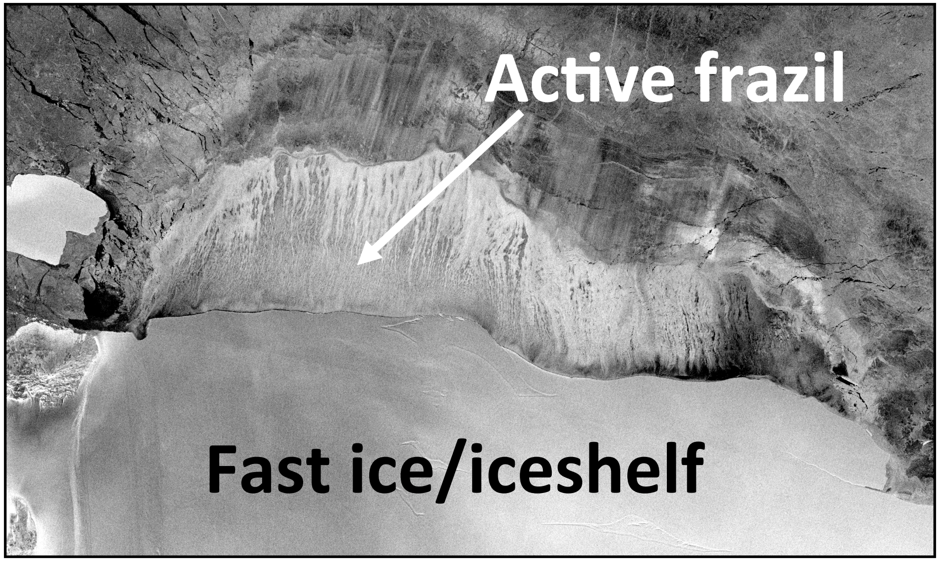


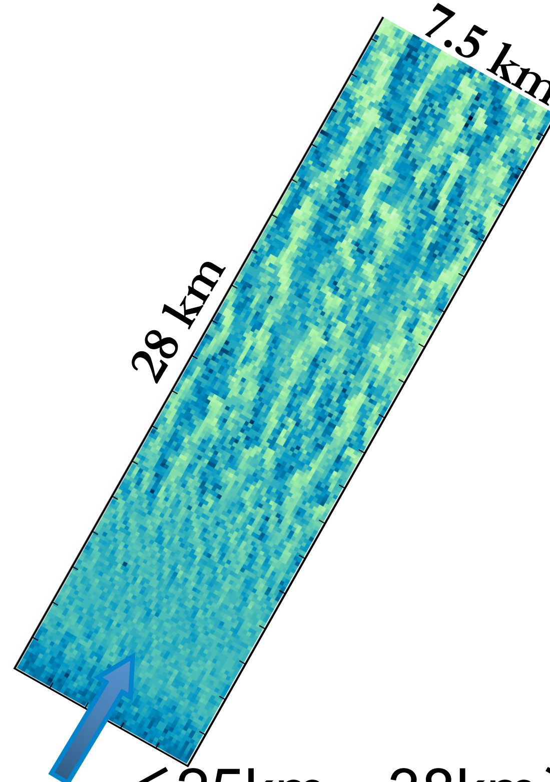
Developing polynya experiment: (by Kazuki Nakata, Ph.D. thesis)



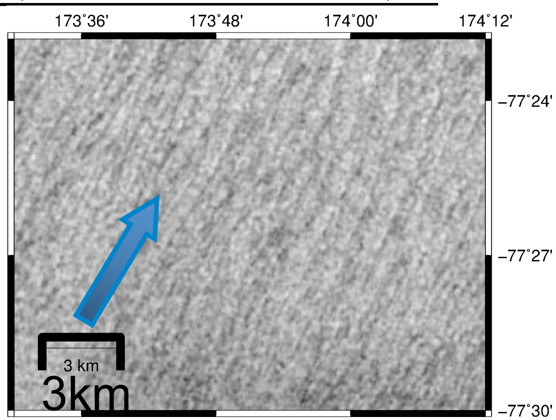
- Under water frazil ice down to 80m depth
- The streak structure develops in the active frazil region

Satellite image active polynya
(day with 15 m/s offshore wind,
air temperature -17℃)

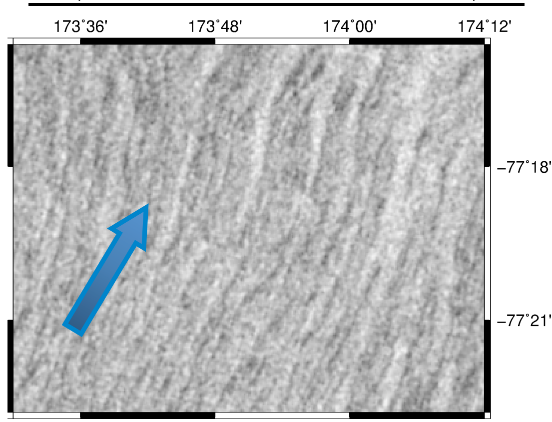




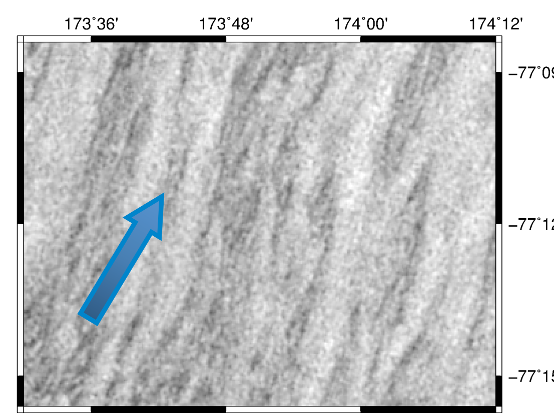
＜coast~13km＞



＜13km～25km＞



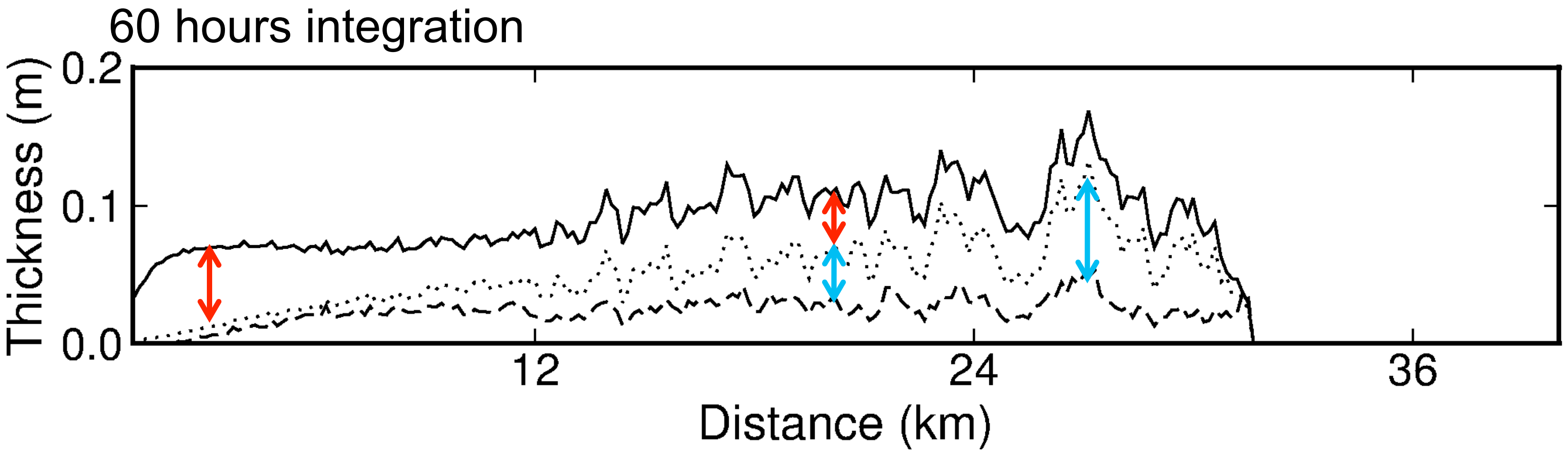
＜25km～38km＞



Modeled streaks are almost identical to the satellite image

Effective thermal ice thickness in the active frazil polynya

Thermal ice thickness ∝ (net air-sea heat flux)$^{-1}$



A. Solid: Equivalent ice thickness corresponds to total ice mass (incl. under water frazil)
B. Dotted: y-averaged effective ice thickness (weighted integ. of ice mass near the surface)
C. Dashed: simulated thermal ice thickness calculated from net heat loss in the model

A-B: Effect of downward turbulent transport of frazil

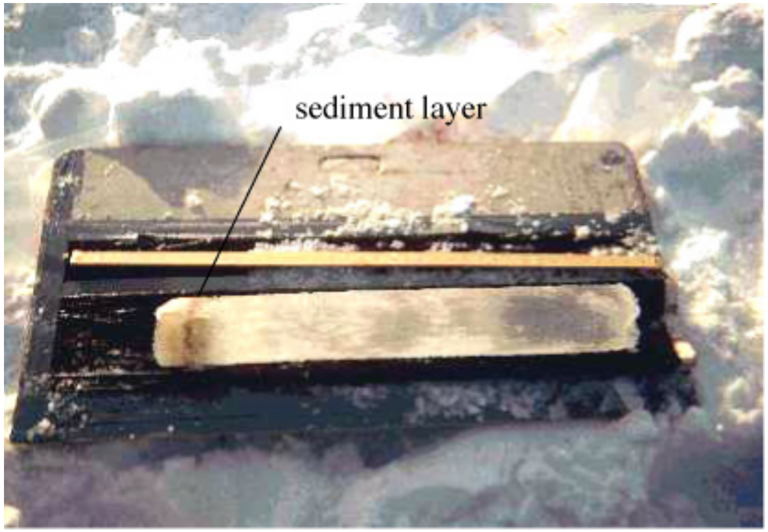
B-C: Effect of streak-structure formation

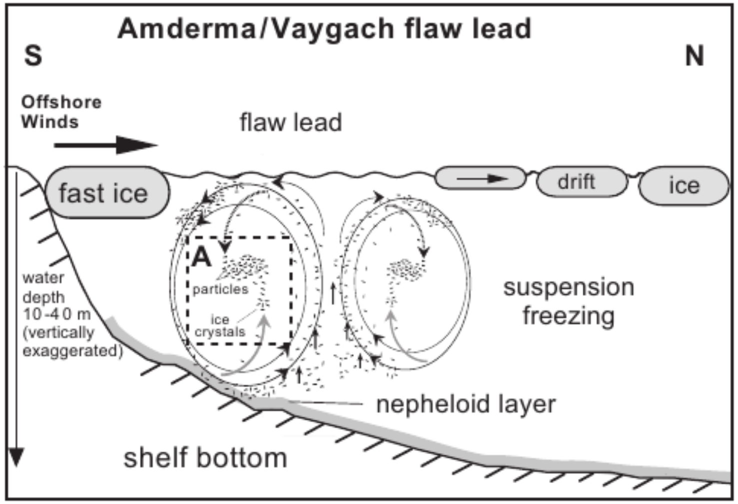
Both **turbulent transport (initial stage/near shore)** and **streak-structure (later stage/near ice edge)** contribute to the higher net ice production in the active polynya under strong wind

The simulated thermal thickness (< 5 cm) is quantitatively consistent with satellite (MODIS) brightness temperature in the active polynya

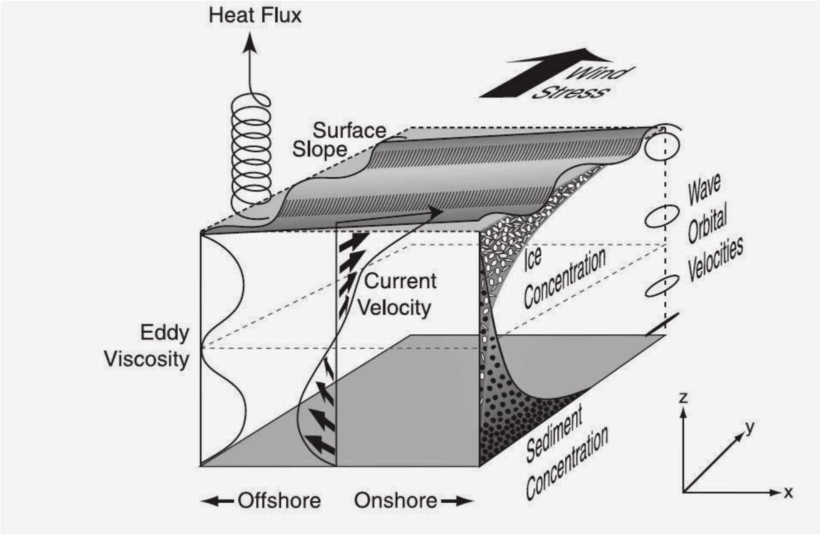
Sediments in Sea ice

- Sea ice (sometimes) contains a lot of **small grain sediments**
  - ✓ Surface albedo decline, can enhance melting.
  - ✓ Transport of trace elements, important on **ocean bio-geochemistry**.
- Possible origins of sediments in sea ice:
  - ✓ Dust from continents (fallen with snows).
  - ✓ **Suspended from ocean floor and entrained** (Nurnberg et al., 1994)





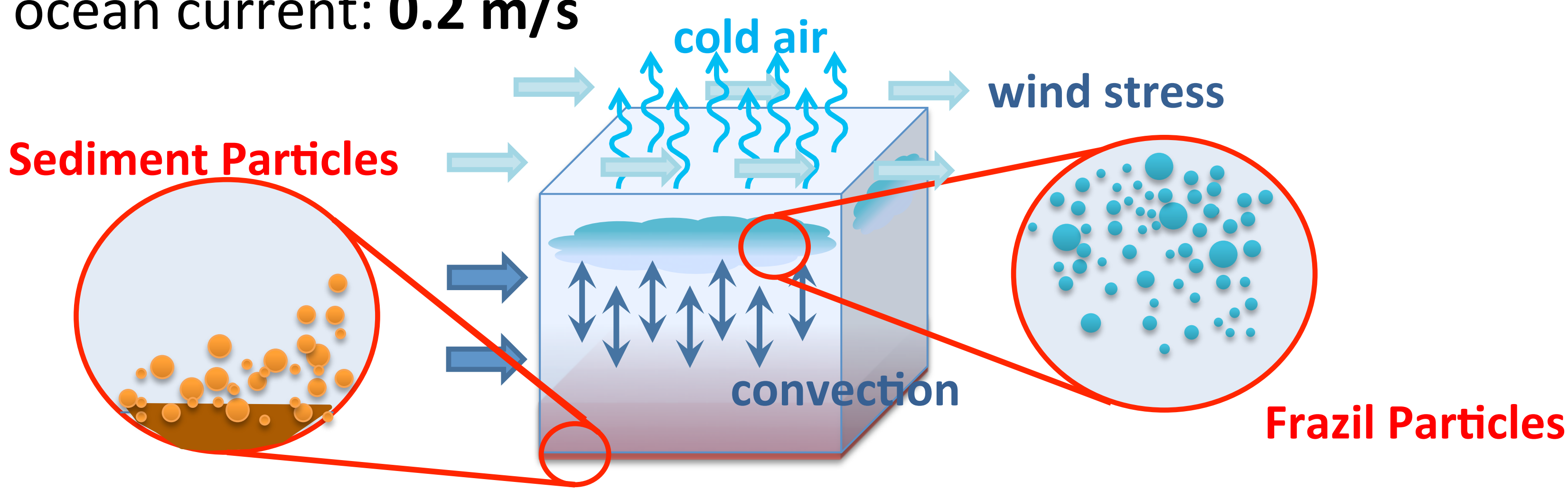
Dethlef and Kuhlmann (2009)



Sherwood et al. (2009)

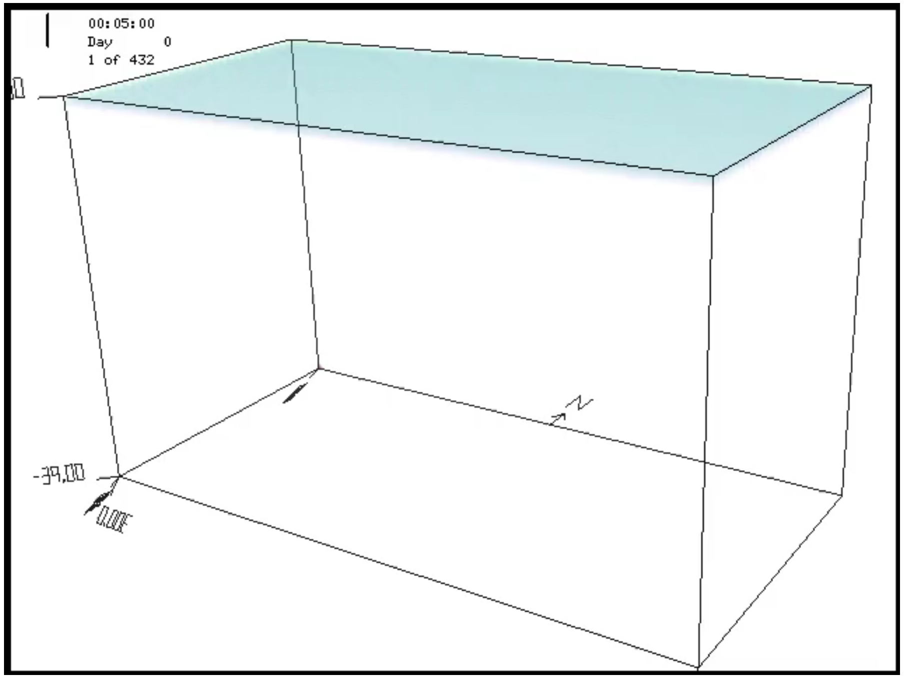
A simple idealized experiment

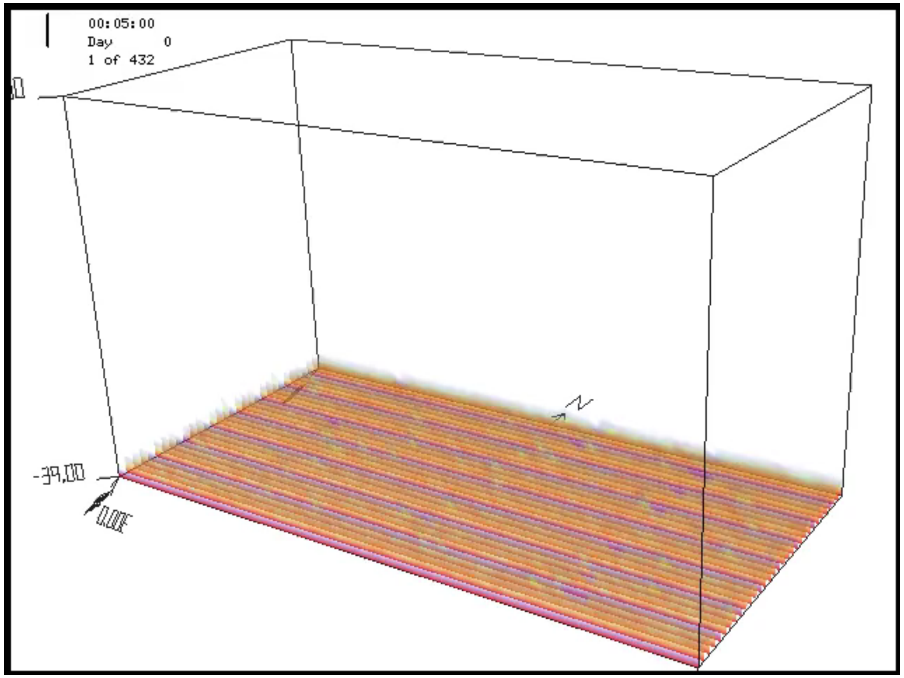
- Ocean component: kinaco (nonhydrostatic, Matsumura and Hasumi, 2008)
  + Lagrangian frazil ice component (developed in the present study)
- Domain: 64m x 32m x 40m, horizontally periodic boundaries.
- Resolution: 1m x 1m x 1m
- Subgrid-model: Smagorinsky-type LES, C is reduced at z < 10m
- Initial condition: Θ = -1.6℃, S = 30psu uniform
- Air temperature: **-20℃** (Up to **～730 W/m²** heat flux at the open water)
- Wind forcing: **5 m/s**
- Initial ocean current: **0.2 m/s**



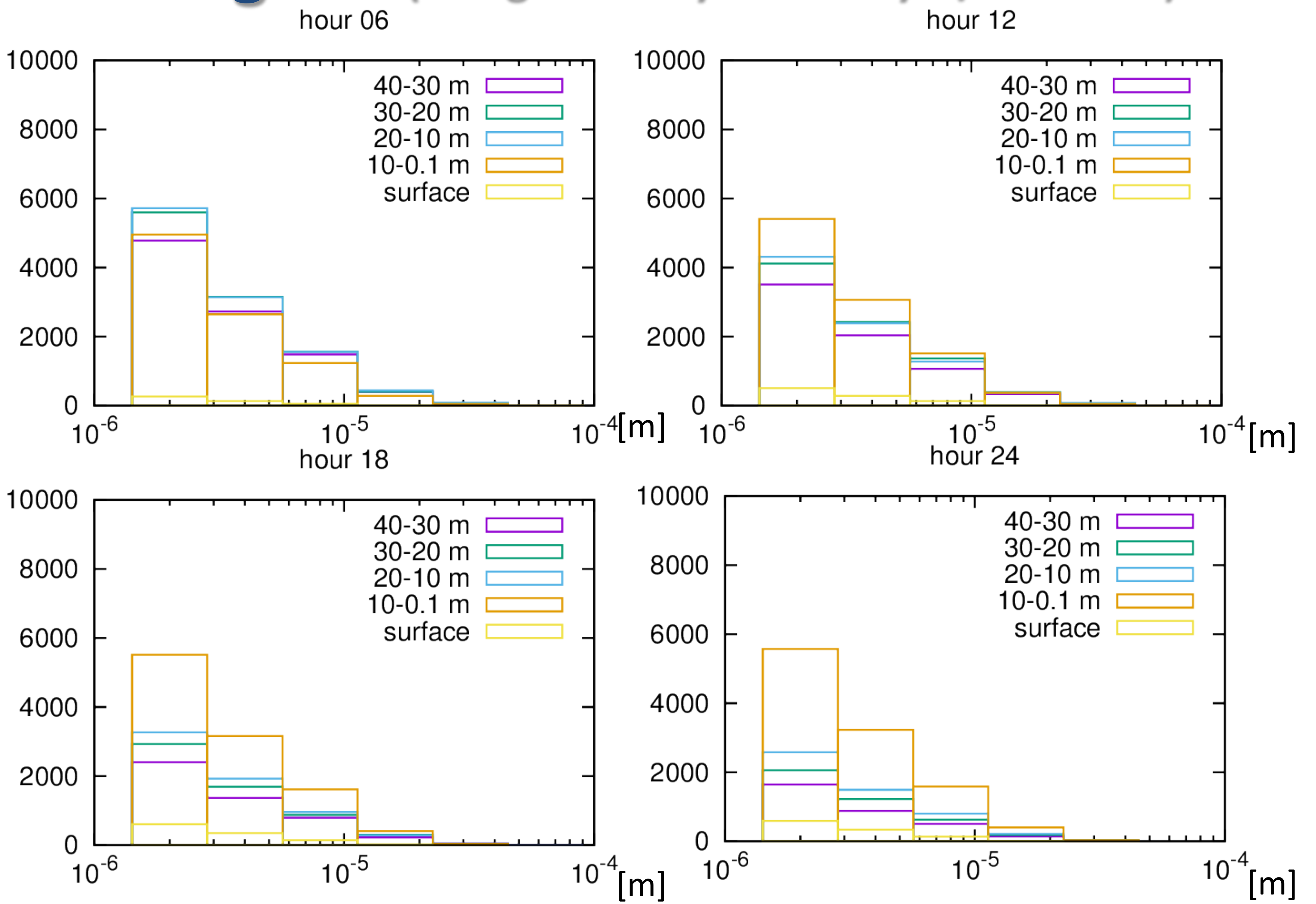
Results

L) Frazil distribution (log scale, blue 10^{-2} kg/m^3 -- red 10^2 kg/m^3)
R) Sediment distribution





Histogram (categorized by ocean layer/diameter)



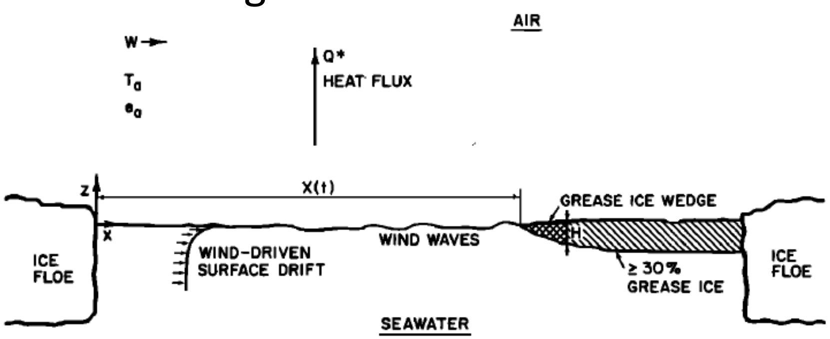
Suspension of sediments > 20μm is rare, consistent with observation

Summary

- A new modeling framework of **frazil ice/grease ice** by using **online Lagrangian particle tracking** is developed
- Modeled Lagrangian particle is treated as a cluster of many crystals
- Simulate thermodynamic grows of each particles
- Parameterize buoyant rise velocity, turbulent diffusion, enhanced molecular viscosity, insulating effects etc.
- Successfully simulate the behavior of underwater frazil ice and their transition to the surface grease ice cover
  - ✓ Vertical motion of underwater frazil ice induce latent heat transport
  - ✓ Potential supercooling is realized due to the freezing point decline with depth
  - ✓ Frazil ice model retains open water relatively longer periods and hence net heat loss is increased compared with solid ice model (~30% greater ice production in the initial 24h)
- Large domain polynya experiments represents streak-like structure of grease ice
- **Sediment entrainment** is a key topic of the future works

Future works

- More precise treatment of crystal size spectrum:
  - ✓ Very sensitive to the grows/melt rate and rise velocity
  - ✓ Should be investigated by direct observation.
- In-situ supercooling state:
  - ✓ Relaxed in a single time step (1sec.) in the present model.
  - ✓ Up to O(10) mK supercooling is observed in reality.
  - ✓ What is seeding nuclei? How many?
- Consolidation:
  - ✓ Transit to solid ice (columnar grows) when frazil volume fraction in the grease ice layere becomes sufficiently high (～30%).
  - ✓ Essential to the polynya opening/closing and refreezing of leads.



Bauer and Martine (1983)n

- Coupled with wave dynamics model
  - ✓ Simulate pancake ice formation
  - ✓ Frazil streaks induced by Langmuir circulation