Formation of ice bands by wind

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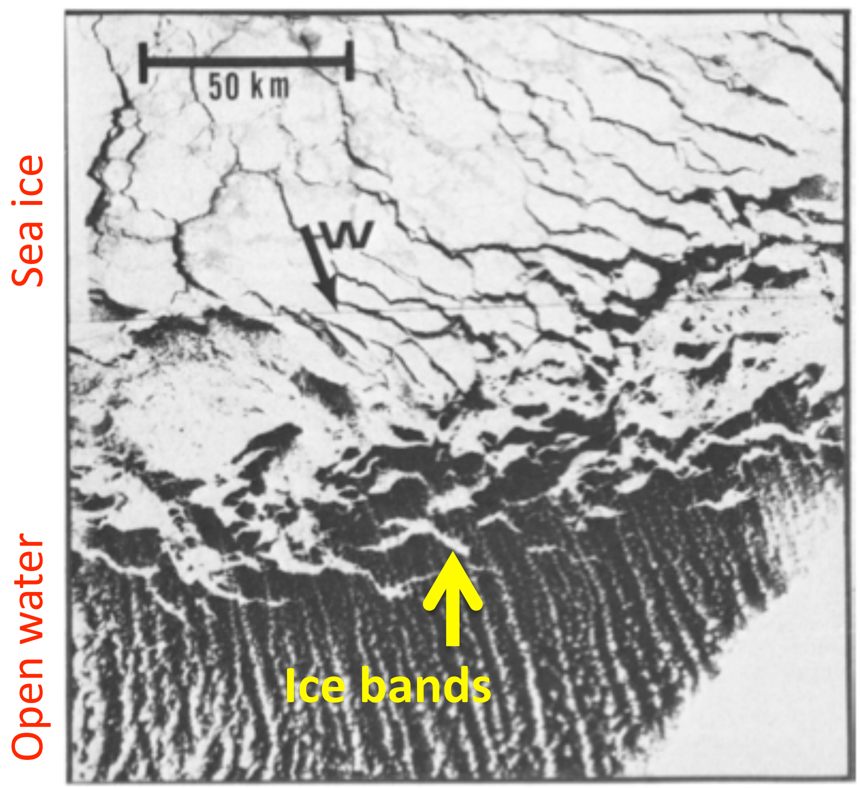
Sea ice in the Sea of Okhotsk.

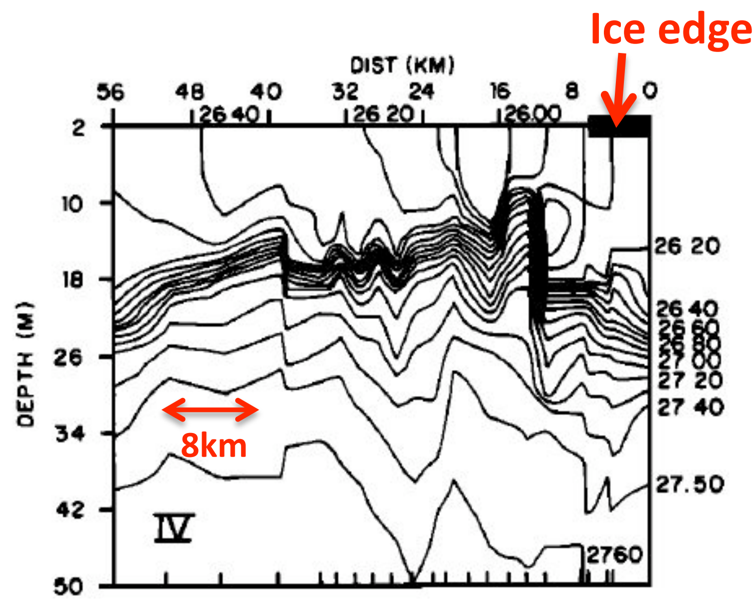
Goals

- Propose a mechanism for the formation of ice bands at the ice edge.
- Are ice bands and vertical motions below them resolved in Ocean-ice GCMs ?

Ice bands from satellite, and wave motion below ice edge



Ice edge in the Bering Sea. (Muench et al., 1983)

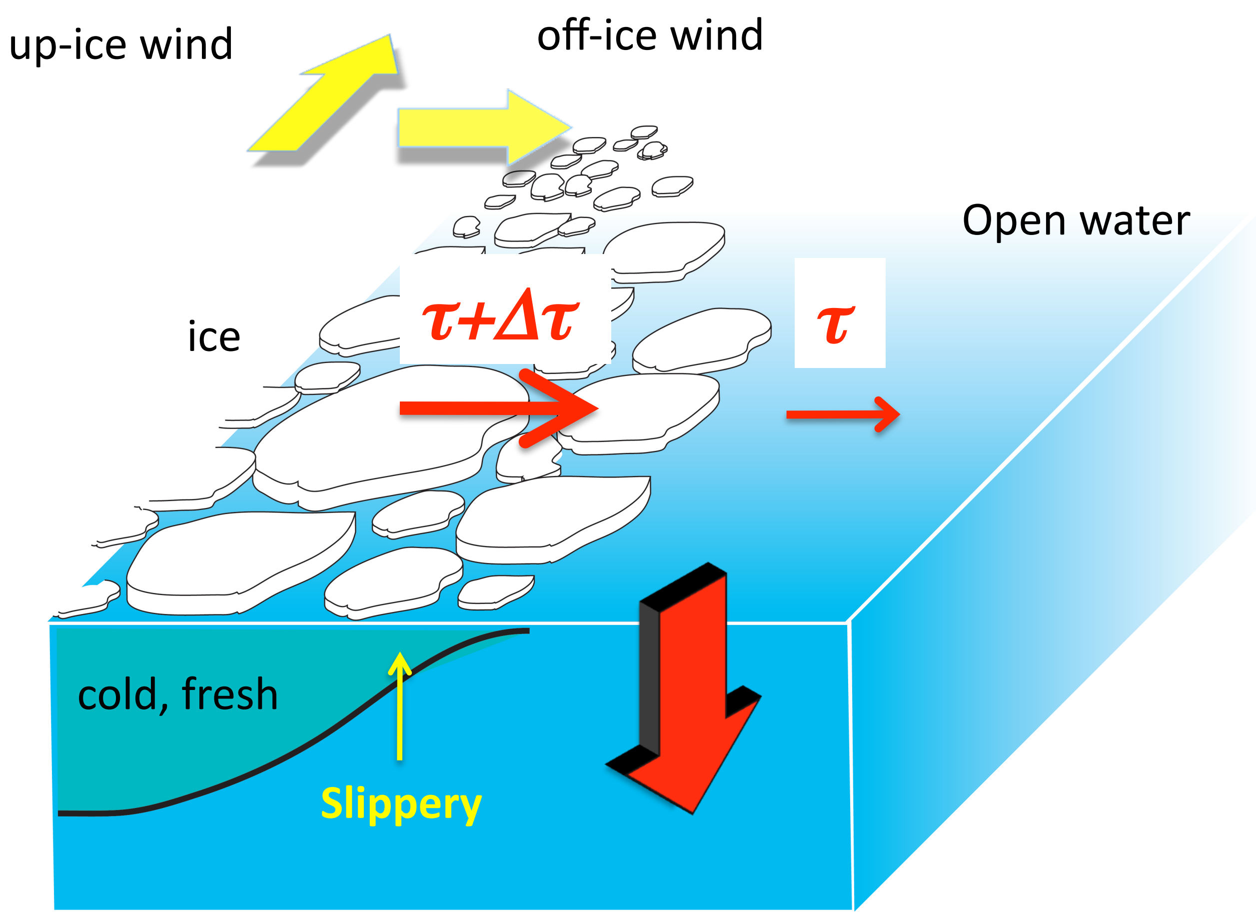


Isopycnals observed in the Greenland Sea (Johannesen et al., 1983)

Mechanisms for ice-band generation :

- Wave pressure radiation (Wadhams 2000)
- **Lee waves** (Muench 1983; Sjoberg and Mork 1985)

Response of ice to wind



Downwelling.

Moving stress. ➔ Similar to hurricane passing (Geisler, 1970). Lee waves form when $U > c_n$.

Is the ice-edge velocity U larger than the baroclinic phase velocity c_n ?

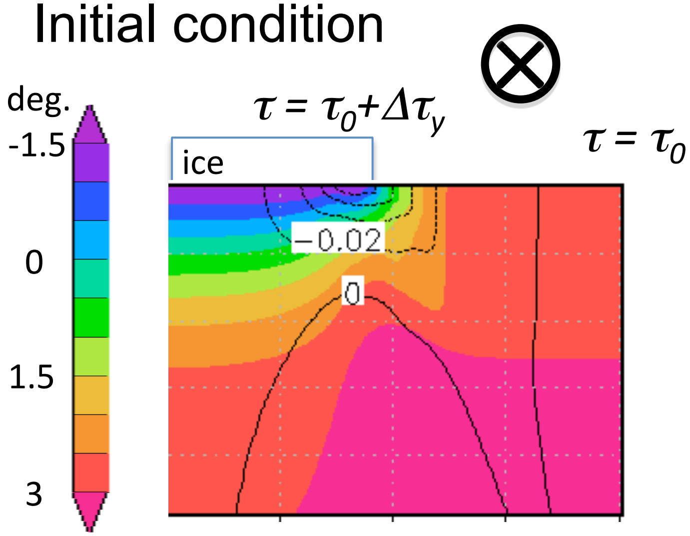
Past studies

- Muench (1983)
  - Analytical study with a two-layer model. No ice physics. Off-ice wind.
- Sjoberg and Mork (1985)
  - Numerical study with a two-layer model. No ice physics. Up-ice wind.
- Hakkinen (1986)
  - Numerical study with a reduced gravity model + ice dynamics model. Time-dependent wind.

This study : Responses of continuously stratified ocean and coupled ice-ocean mechanisms.

Ice-ocean coupled model

Initial condition



Momentum equation

$$\frac{\partial \tilde{u}_{ice}}{\partial t} - jf\tilde{u}_{ice} = \frac{\tilde{\tau}_{ai}}{\rho_{ice} h} + \frac{\tilde{\tau}_{iw}}{\rho_{ice} h} - g\tilde{\nabla}\eta$$

Ice-ocean heat transfer

$$L_i \frac{dh}{dt} = -\beta u^* \Delta T$$

L_i : latent heat of ice fusion
h : ice thickness
u^* : friction velocity

Ocean model	Princeton Ocean Model
Ice model	Ice dynamics (EVP) + melt/freeze
Domain	250km × 300m (x-z)
DX	250m
DZ	1m
B.C.	Radiation

Lee-wave generation by moving ice edge

Non-dimensionalised equation for *n*-mode elevation η_n by normal mode solution.

$$-\left(1-U_*^{2}\right)\frac{\partial^2 \eta_{*n}}{\partial \zeta_*^{2}}-\eta_{*n}=\begin{cases}-D\delta(\zeta_*) & \text{Off-ice wind}\\ DU_*^{-1}H_0(-\zeta_*) & \text{Up-ice wind}\end{cases}$$

➔ Wave solution when $U > c_n$.

$$D=\frac{\Delta\tau}{fg\rho_w H^F},\quad U_* = U / c_n,\quad \zeta_* = \zeta / R,\quad \eta_* = \eta / H^F$$

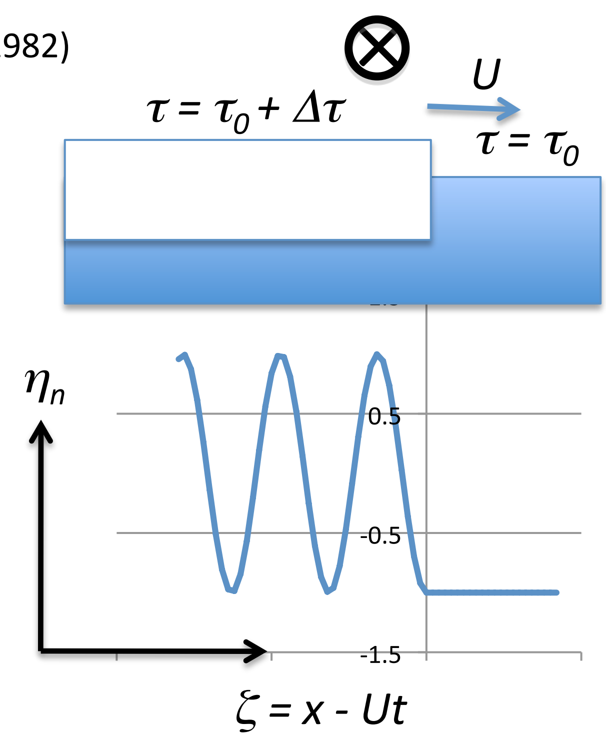
U : ice edge speed
$\Delta\tau$: stress gap
H^F : equivalent forcing depth (Gill, 1982)

Super-critical solution ($U > c_n$)

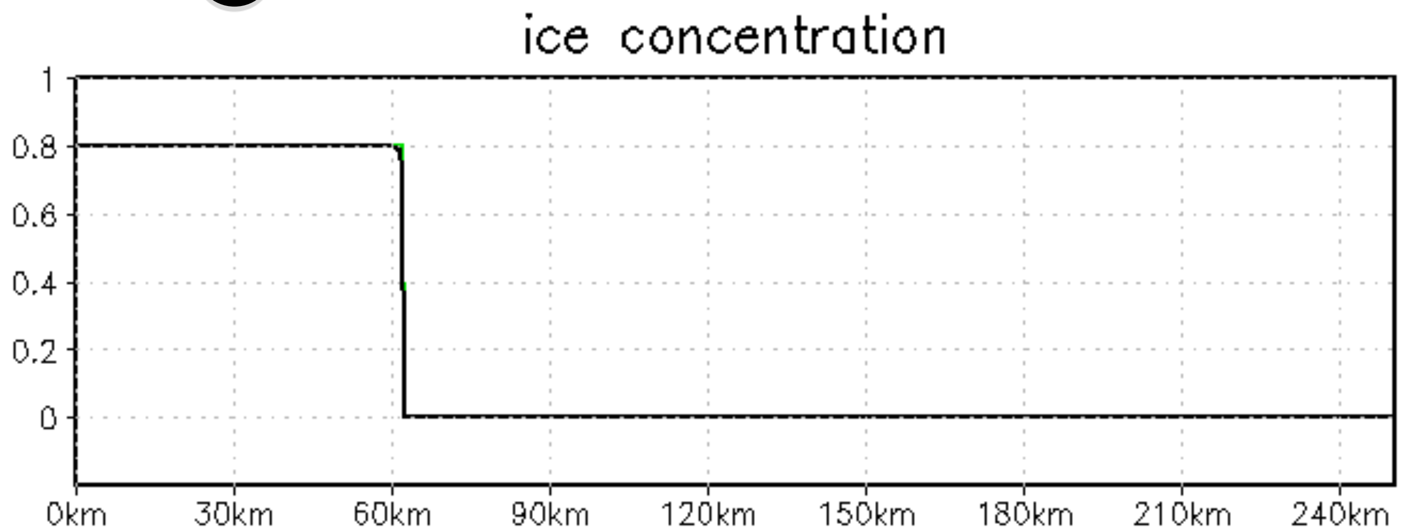
$$\frac{\eta_n}{D_n}=\begin{cases}-1 & \zeta>0\\ -\cos(\kappa_F\zeta) & \zeta<0\end{cases}$$

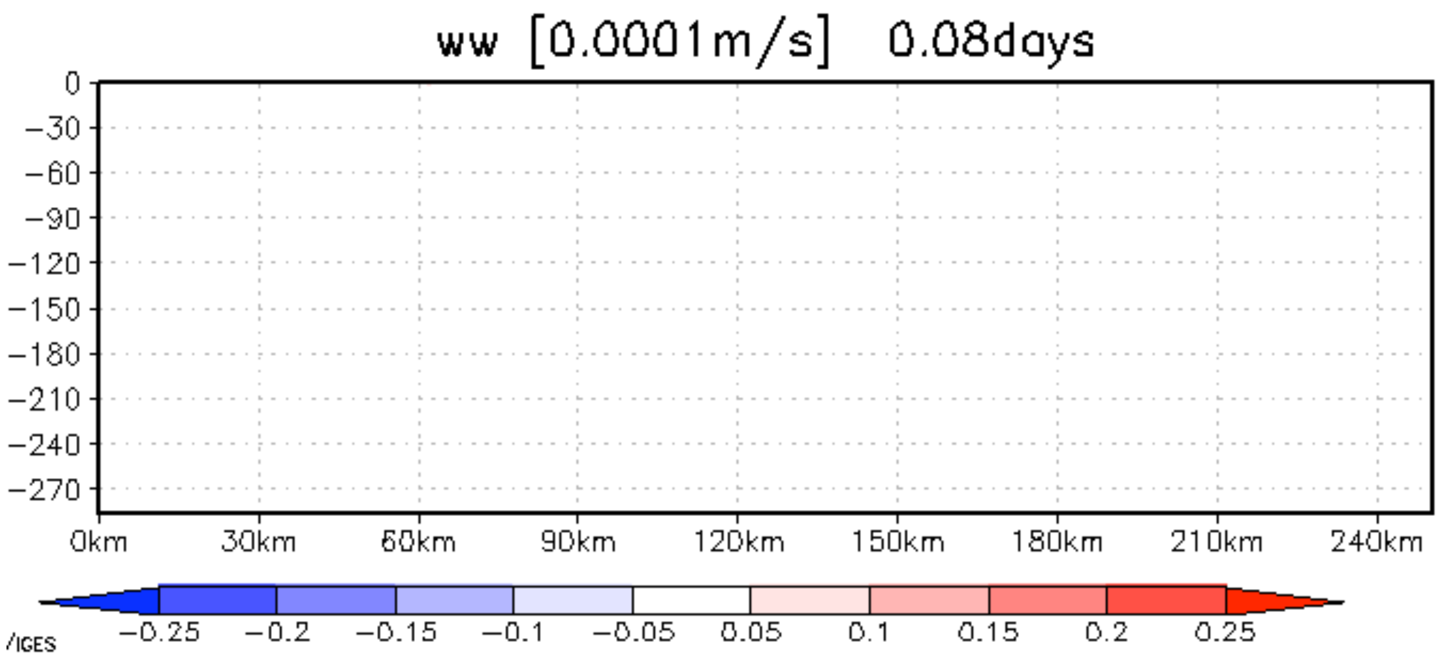
$$\kappa_F^{\ 2} = f^2/(U^2-c_n^{\ 2})$$ Wavenumber

$$|w(-H_{mix})| = \frac{gD_n\kappa^3 U H_{mix}}{(\kappa U)^2 - f^2}$$ Amplitude of vertical motion



5m/s wind ⊗


ice concentration
1
0.8
0.6
0.4
0.2
0
0km
30km
60km
90km
120km
150km
180km
210km
240km


ww [0.0001m/s] 0.08days
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−90
−120
−150
−180
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180km
210km
240km
−0.25
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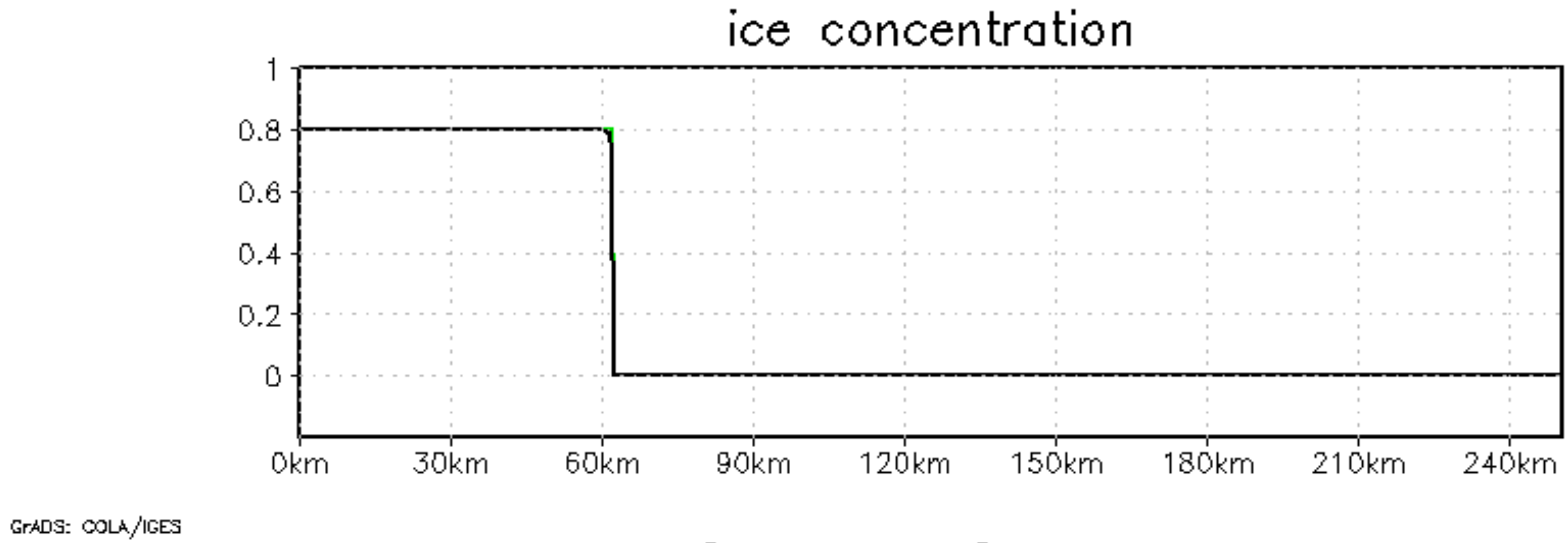
ice concentration
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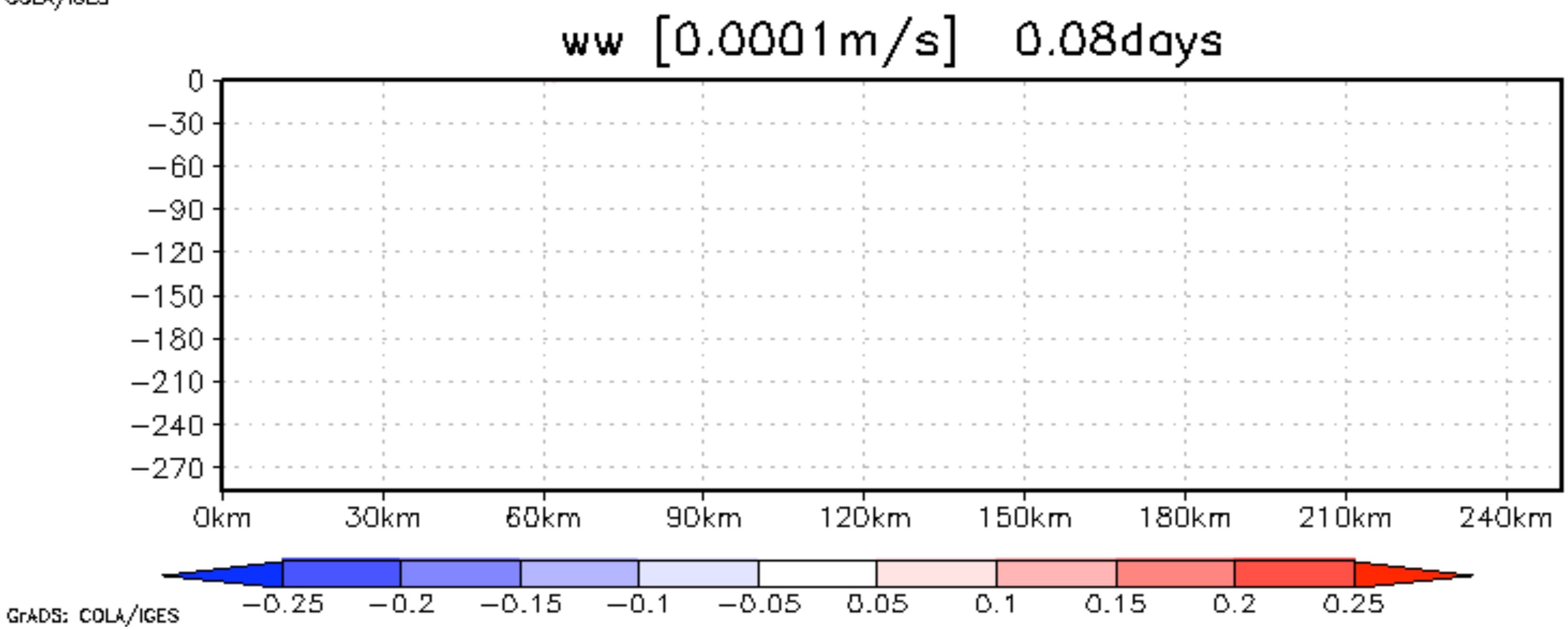
GrADS: COLA/IGES


ww [0.0001m/s] 0.08days
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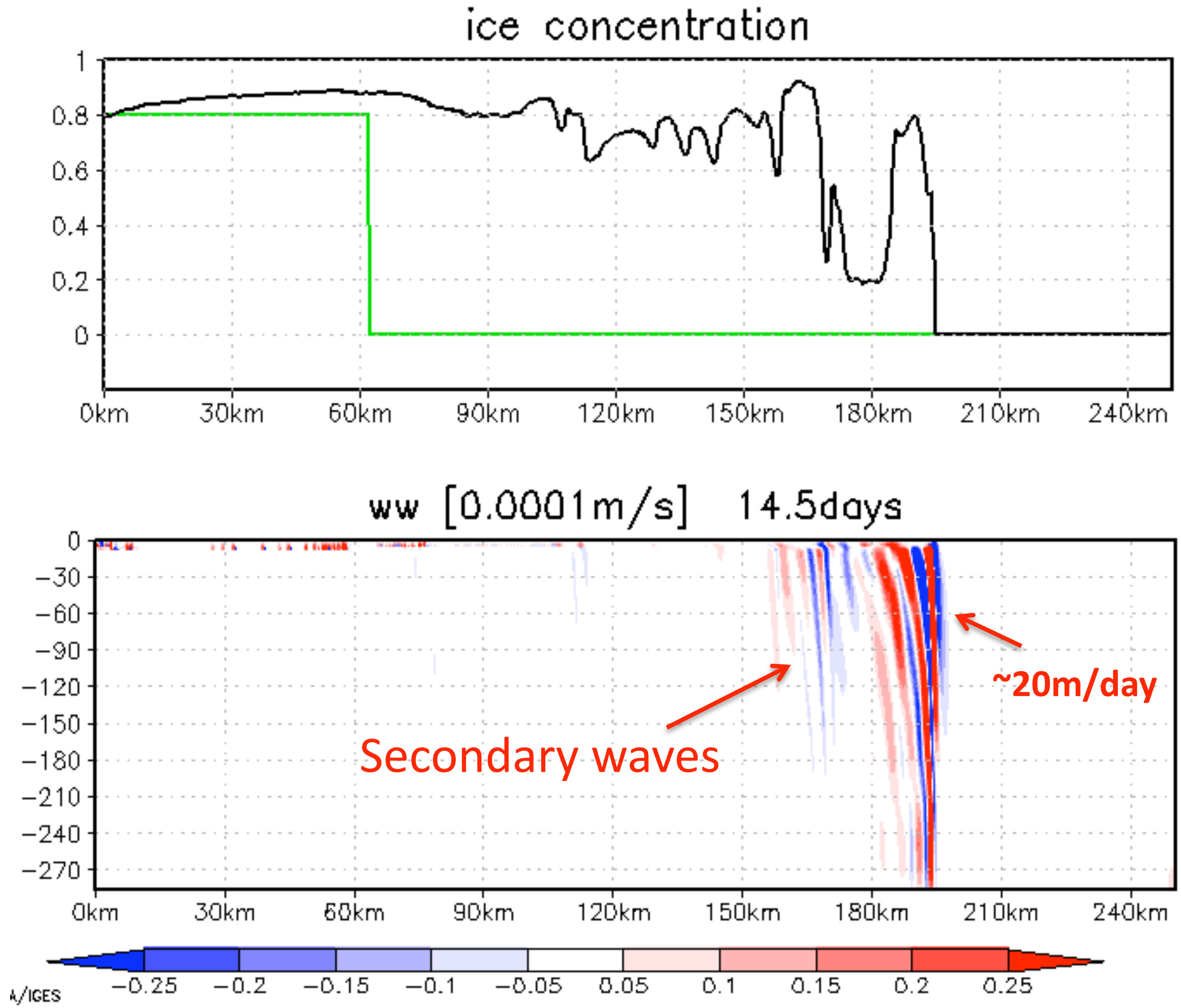
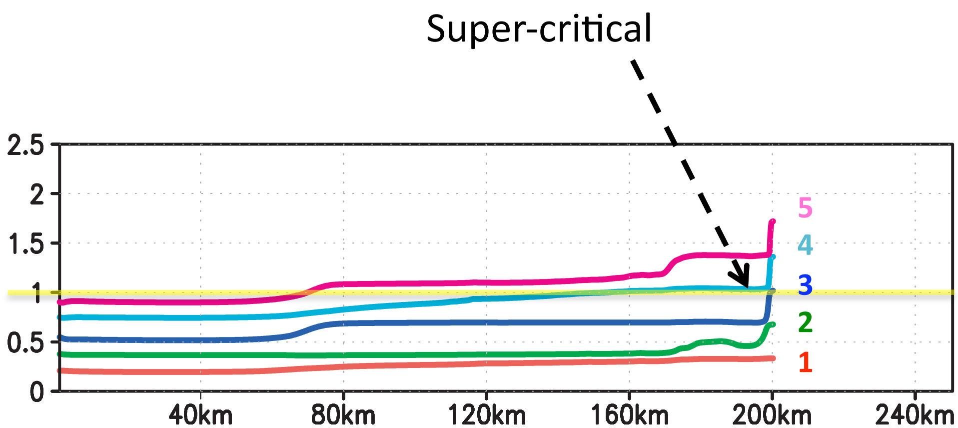
GrADS: COLA/IGES

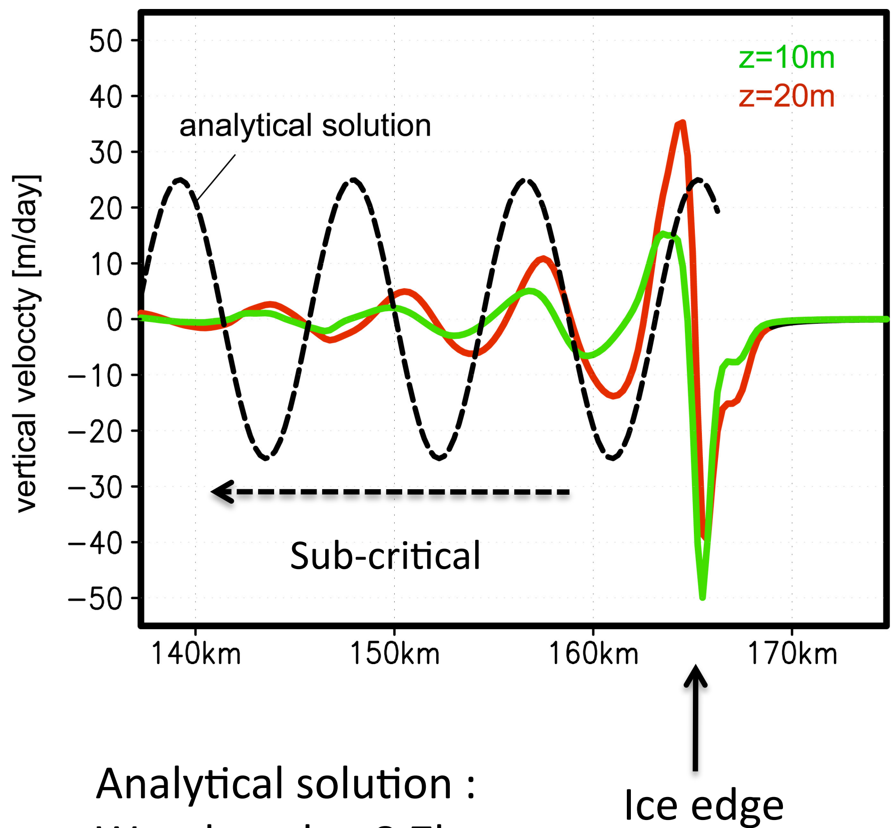


- Ice band is ~15km. Vertical motions with ~7km wavelength are observed.
- Ice band width is larger than lee wavelength. Why ?

- Super-critical condition in the third mode, $U > c_3$ (left).
- Behind the ice edge, flow is subcritical $U < c_3$, and the waves decayed (right).



Ratio of the ice velocity to the baroclinic phase velocity U/c_n.



Analytical solution :
Wavelength = 8.7km
Amplitude = 25km

Low-pass filtering by ice-water stress

Why width of ice bands is larger than wavelengths of lee waves ?

$$\tau_w \sim -\alpha(\tilde{u}_{ice} - \tilde{u}_w)$$

$$\frac{\partial \tilde{u}_{ice}}{\partial t} - (-\alpha + jf)\tilde{u}_{ice} = \alpha \tilde{u}_w$$

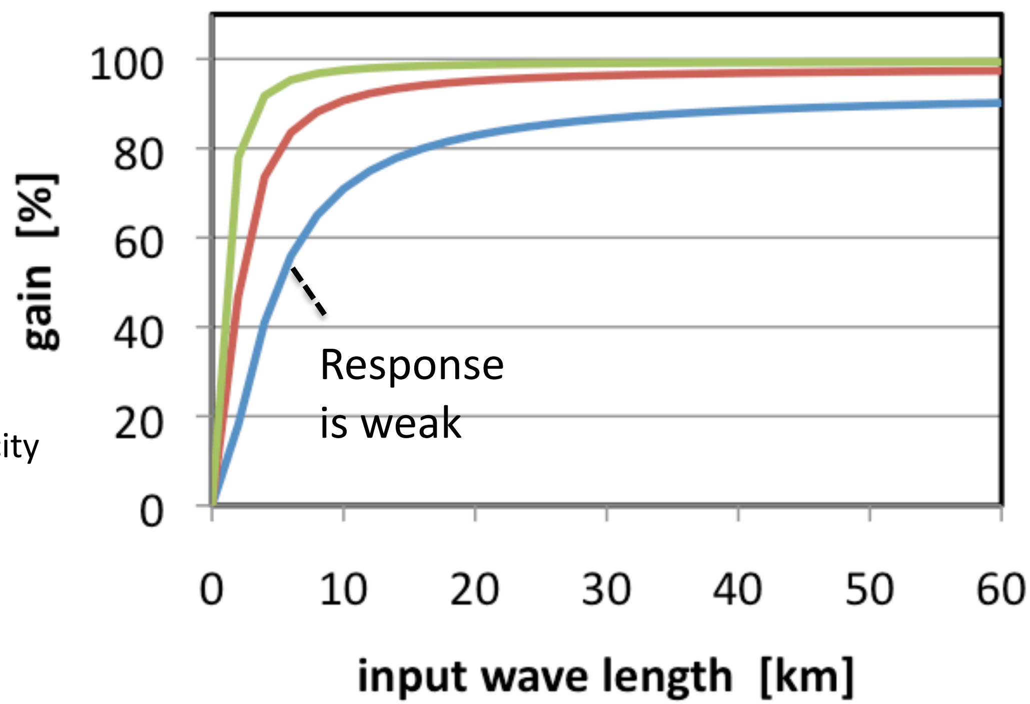
$$\tilde{u}_w \sim \frac{gD\kappa_F f}{(\kappa_F U)^2 - f^2} \exp(j\kappa_F \zeta)$$

Water velocity (given)

$$\tilde{u}_{ice} = \frac{\alpha \tilde{u}_w}{\alpha + j(f + \kappa_F U)}$$

Amplitude gain G

$$G = \left| \frac{\tilde{u}_{ice}}{\tilde{u}_w} \right| = \frac{1}{1 + \beta^2}, \quad \beta = \frac{f + \kappa_F U}{\alpha}$$



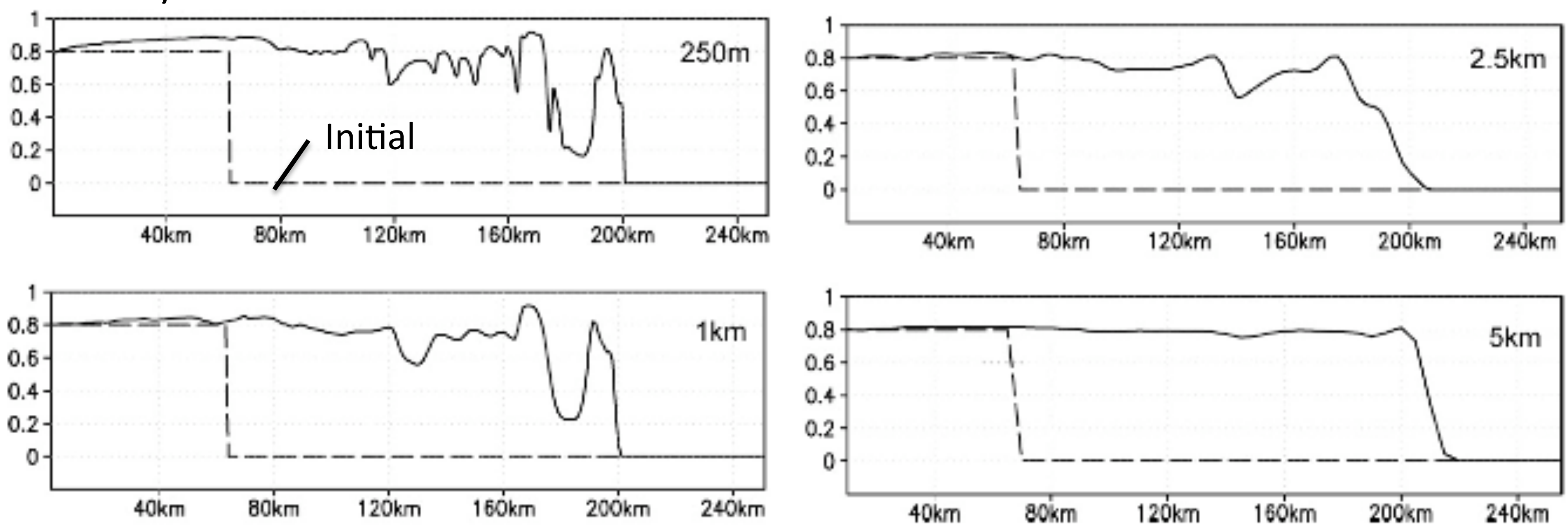
α = 0.3 kg/m^{2}s

α = 0.15 kg/m^{2}s

α = 0.75kg/m^{2}s

Grid size effect 1

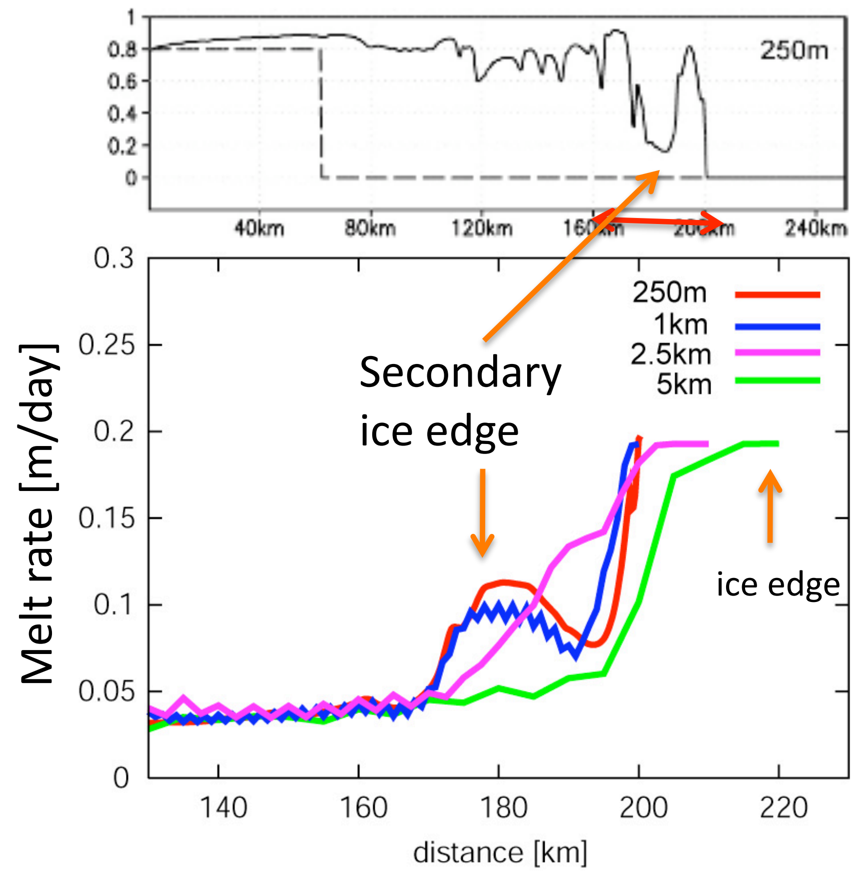
15days after



Ice bands are still formed with1km grid size, but not with 2.5km and 5km.

Grid size effect 2

- Strong *w* at the ice edge was not resolved with coarse grid sizes.
- Secondary peaks in melt rate were found with 250m and 1km grids.
- They were not resolved with 2.5km and 5km, and their ice edges went farther instead.



Summary

- Wind produces a coupled response of ice bands and lee waves.
- Wavelength of lee waves is determined by the ice velocity *U* and the baroclinic phase velocity c_n. On the other hand, wavelength of ice bands becomes longer due to the low-pass filtering effect of ice-water stress.
- A wedge in the first ice band generates secondary lee wave, which produces secondary melting.
- Ice bands were barely resolved with coarse grids (2.5km, 5km).
- Vertical velocity associated with ice bands can influence the deeper layer.
- The coupled process is not resolved with OGCM's grid sizes but it is a potentially important sub-grid process which determines the melt rate in the marginal ice zones.