Submesoscale sea ice-ocean interactions in marginal ice zones

Georgy E Manucharyan

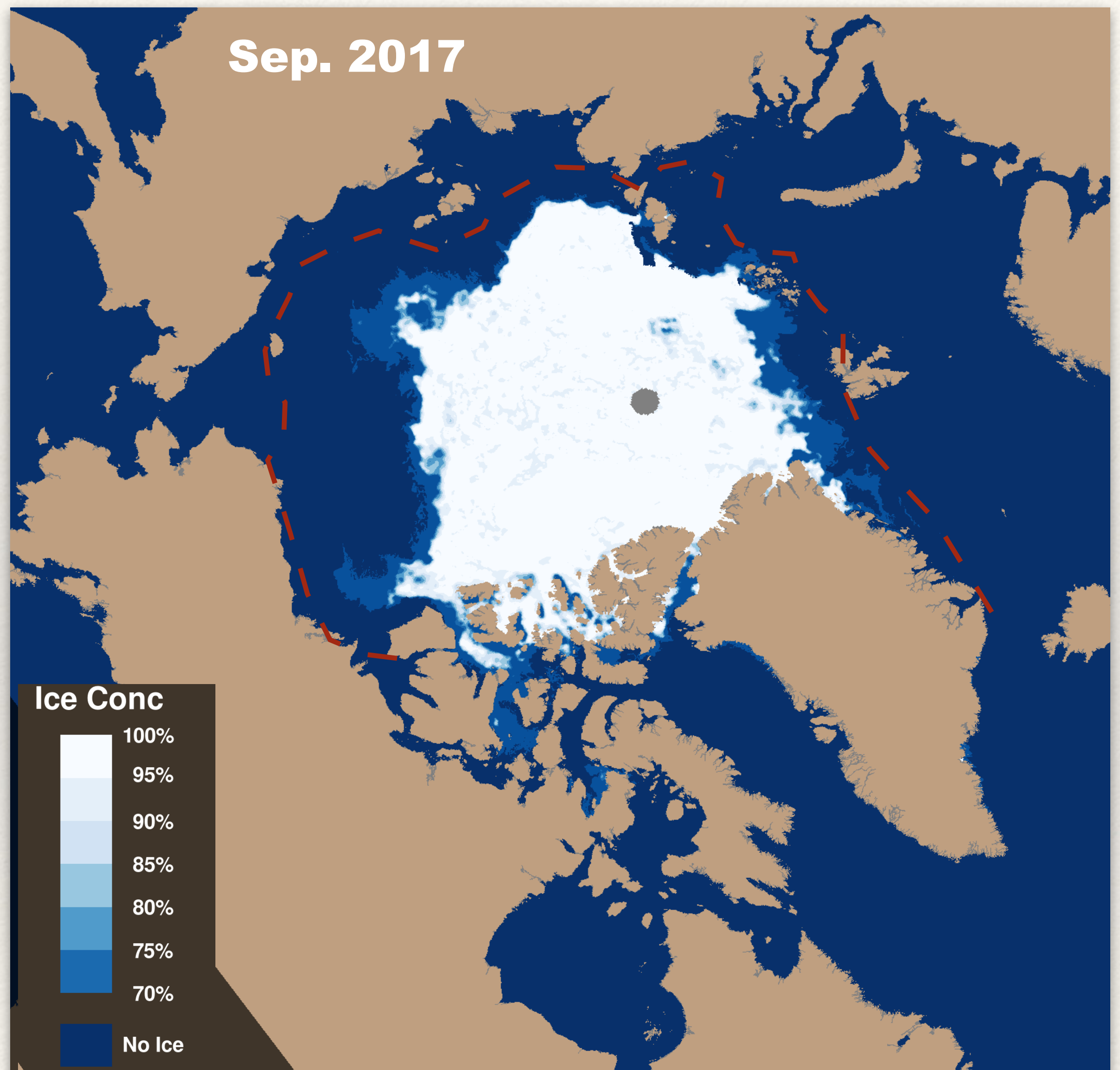
Division of Geological and Planetary Sciences, Caltech

Collaborators: A. Thompson (Caltech), D. Menemenlis (JPL), R. Fajber (U. Toronto)

Sponsors: Stanback Fellowship and Davidow Discovery Fund (Caltech)

worldview.earthdata.nasa.gov

Arctic sea ice state



Data source: MASAM2, Daily 4-Km Arctic Sea Ice Concentration; National Snow and Ice Data Center, CIRES, University of Colorado, Boulder.

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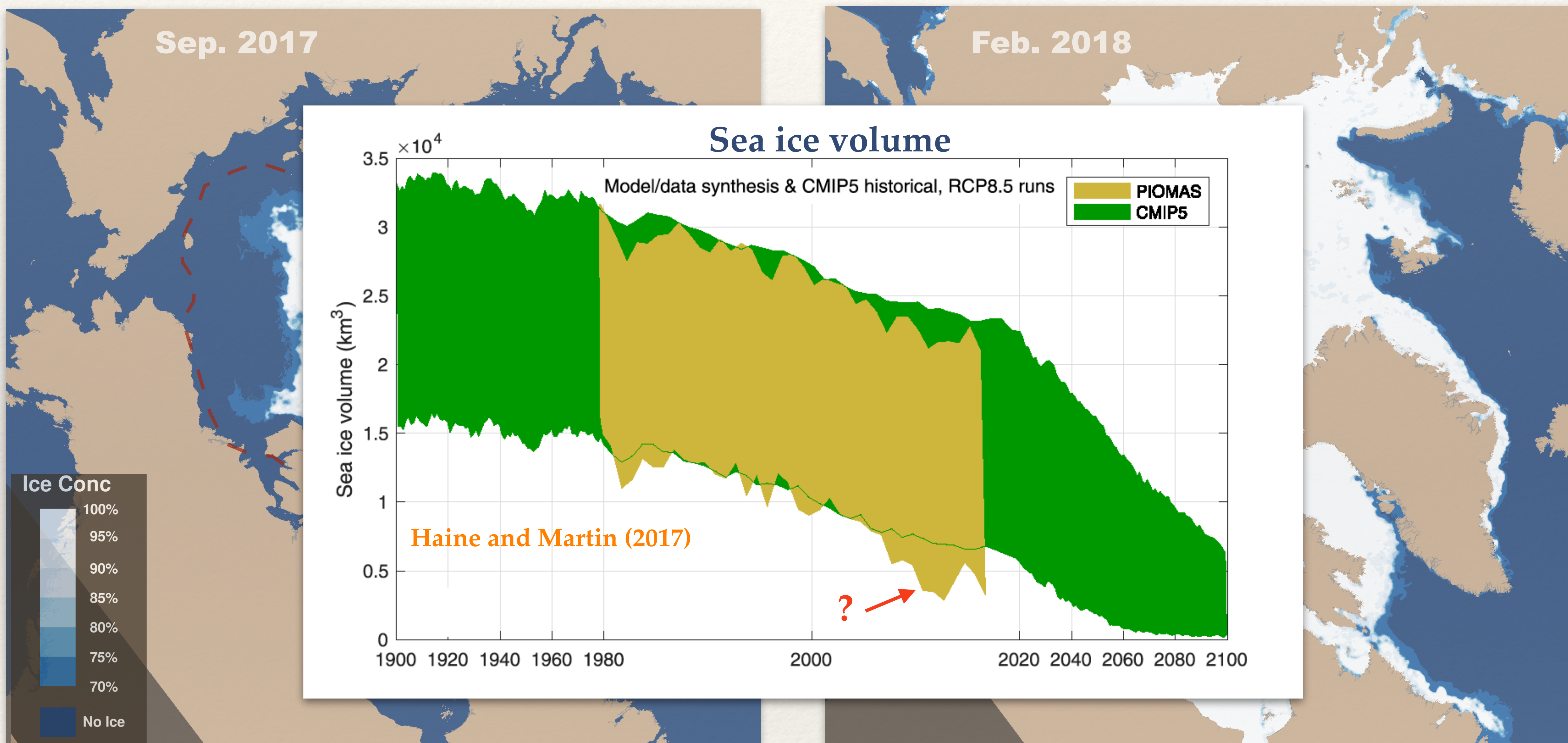

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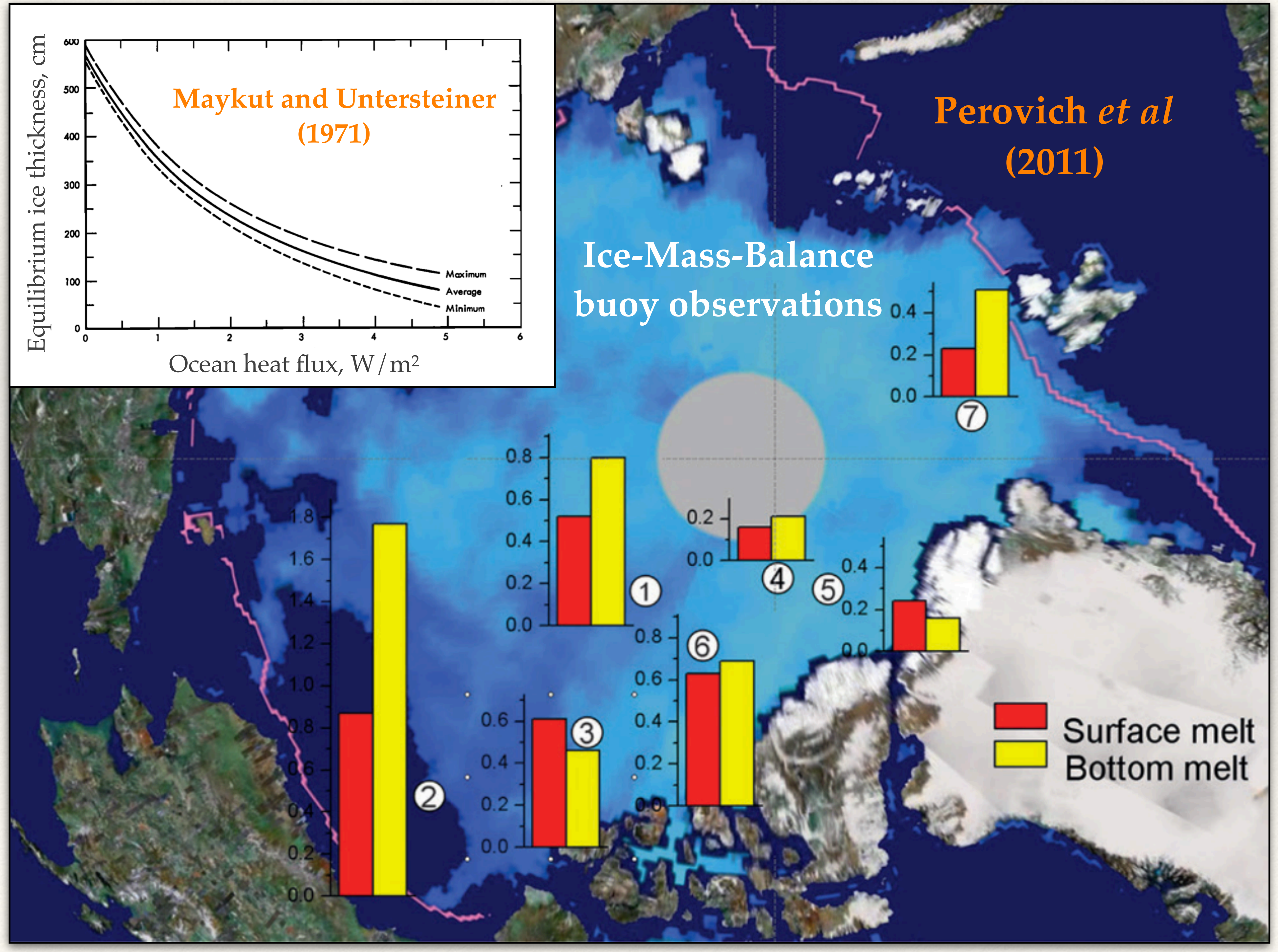
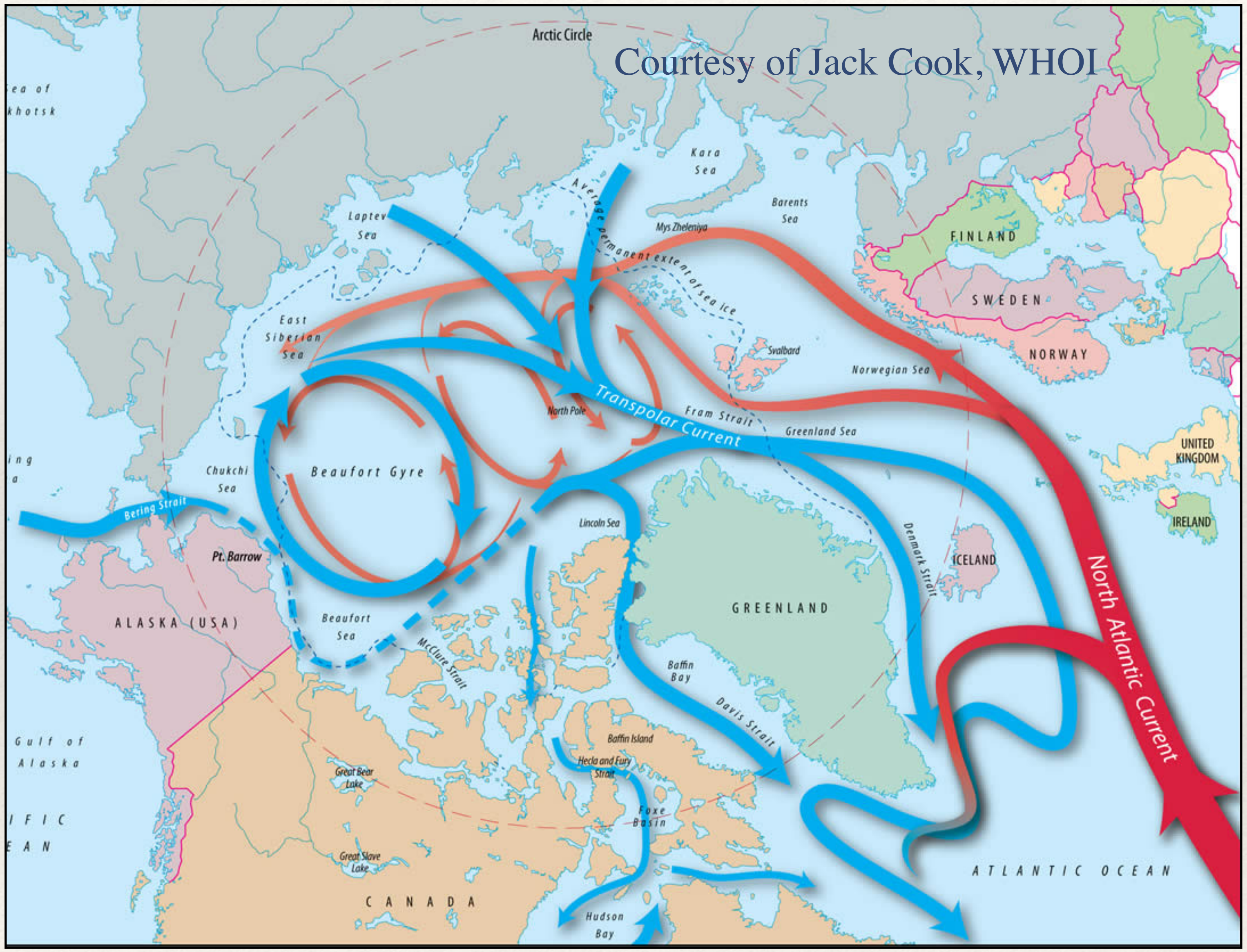
Critical role of ocean heat in Arctic sea ice melt

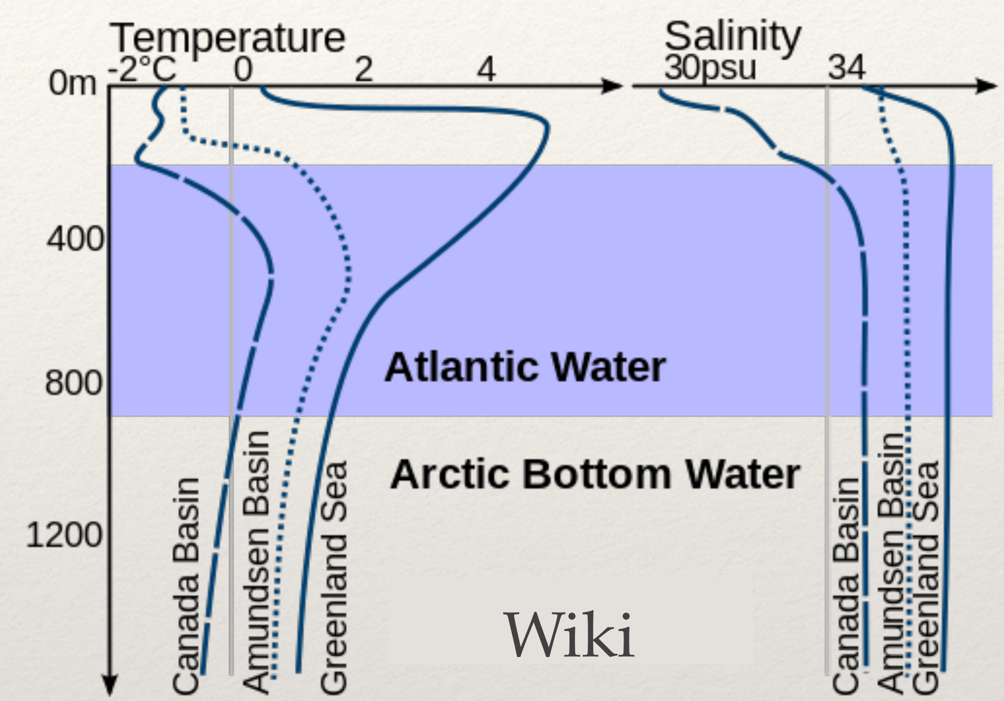


Heat flux that can explain the sea ice **loss** during the past few decades is **≈1 W/m²** (**Kwok & Untersteiner, 2011**)

Seasonal to inter-annual predictions have largest errors in MIZs (**Tietsche et al., 2014**) with extent predictability for only several months (**Stroeve et al., 2014**).

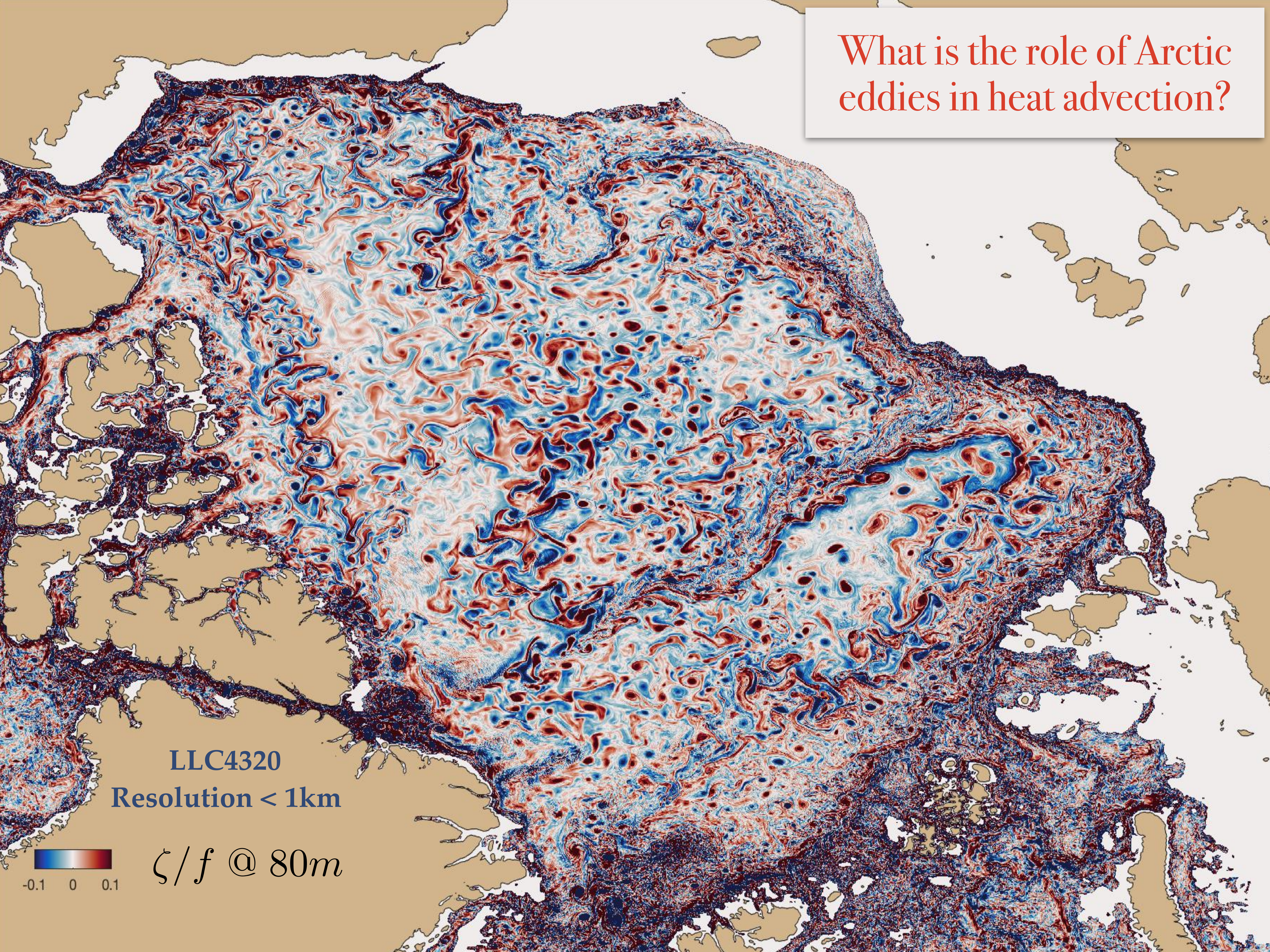
Where does the Arctic Ocean heat come from?





Arctic is salt stratified with heat from Atlantic and Pacific Oceans trapped at depth

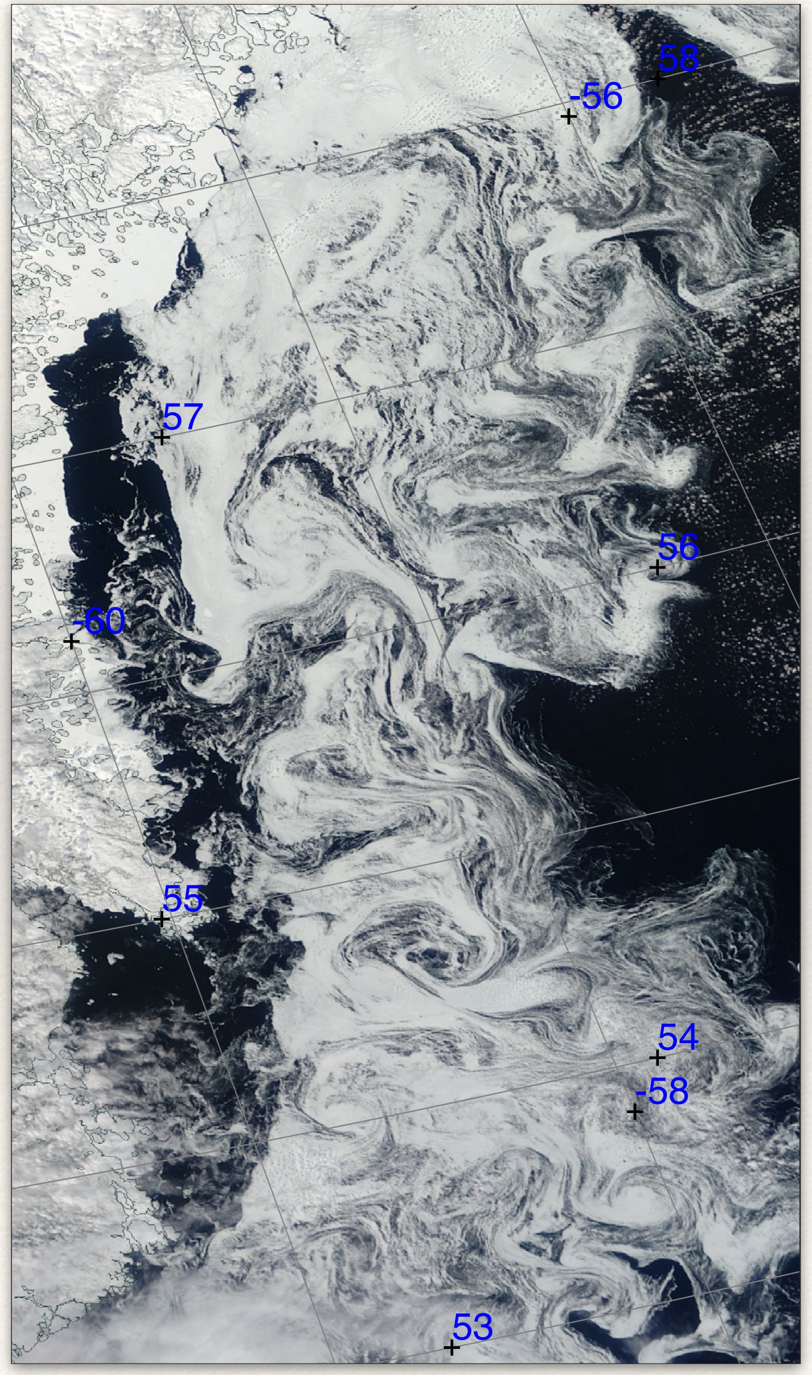
Heat stored in the halocline is an important source during winter


What is the role of Arctic eddies in heat advection?
LLC4320
Resolution < 1km
ζ/f @ $80m$
-0.1
0
0.1

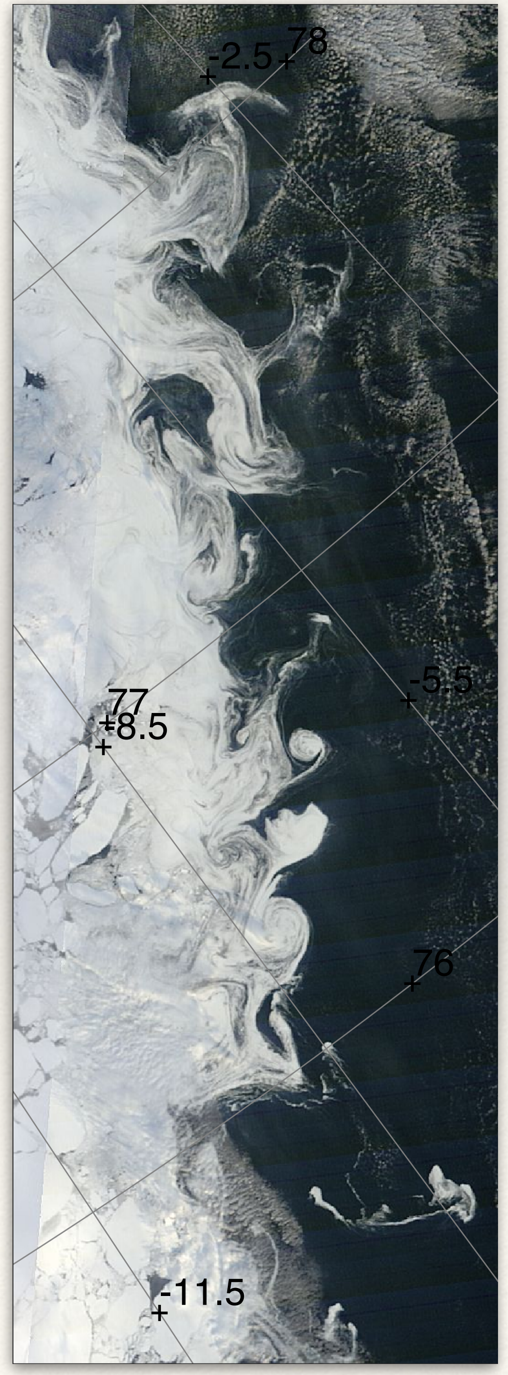
Heavy footprints of oceanic **fronts, eddies and filaments** on **sea ice** distribution in marginal ice zones

Beaufort Gyre from SAR imagery

Labrador Current (MODIS)



Fram St. (MODIS)



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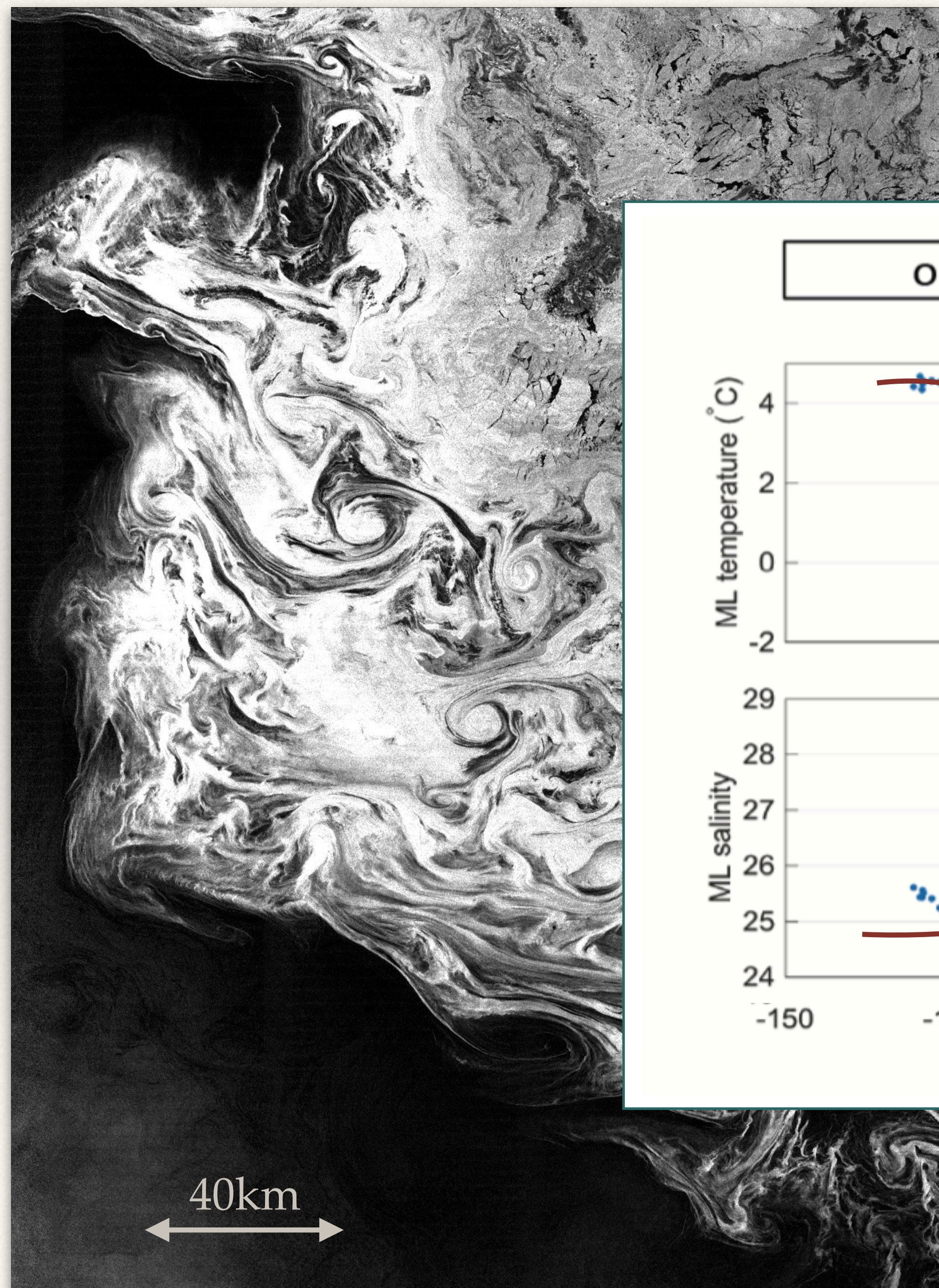

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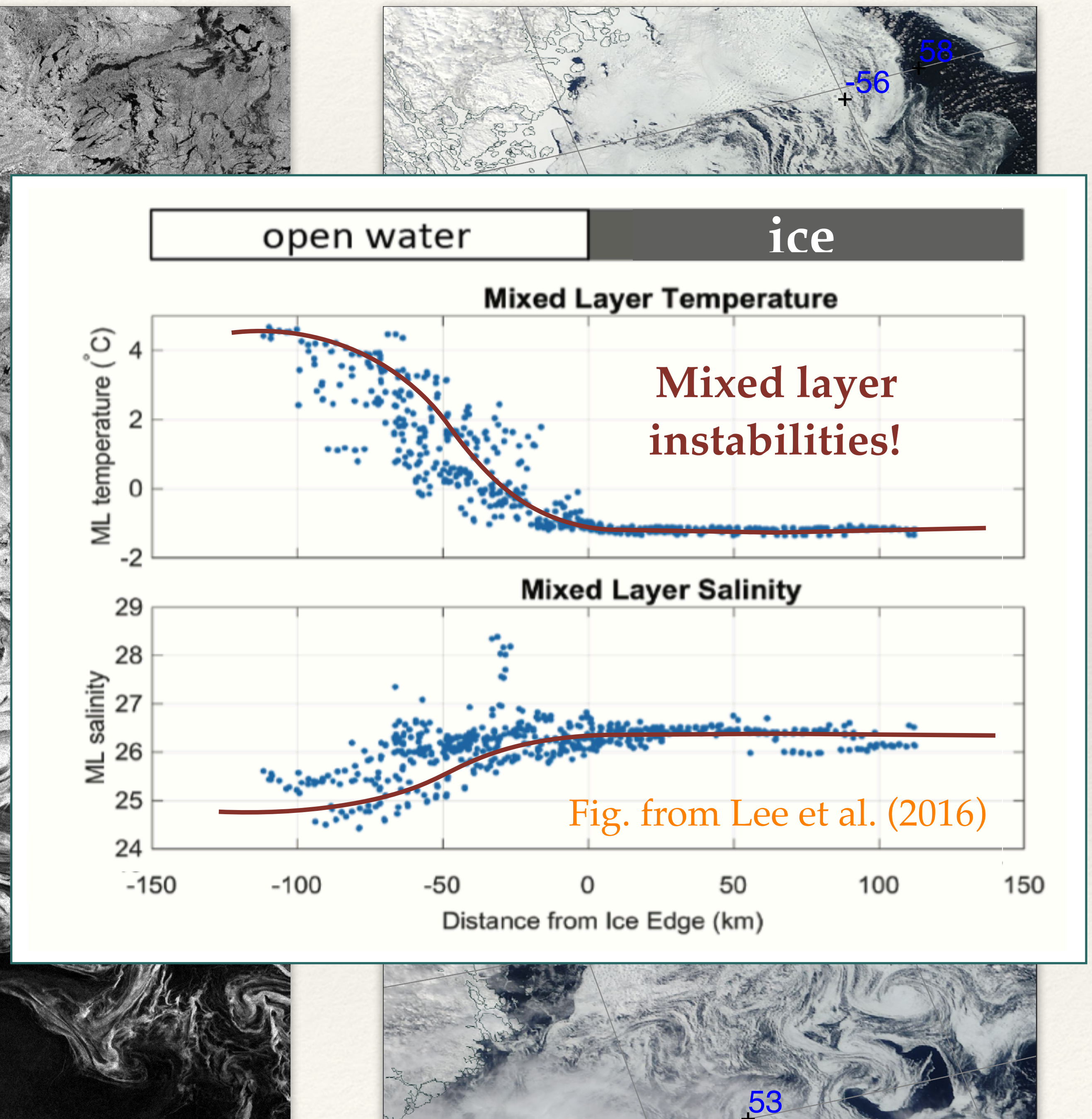

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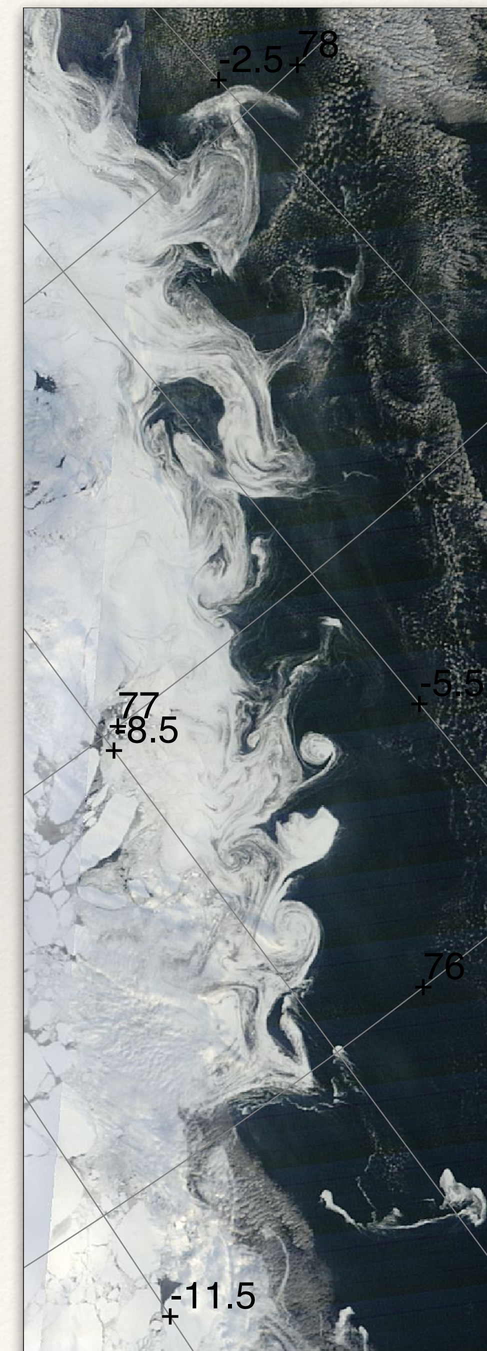
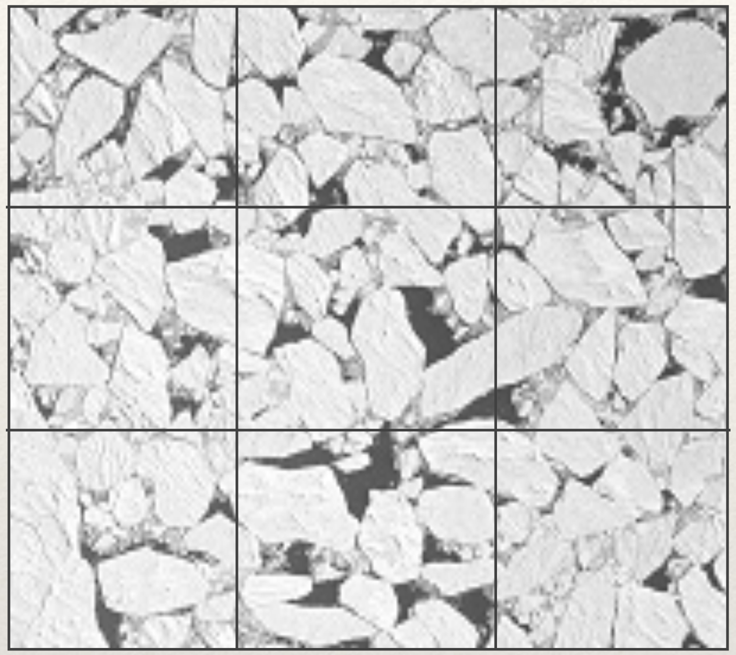


Part I. Sea ice-ocean interactions at eddy scales

Can eddies efficiently redistribute sea ice and enhance vertical heat fluxes? How robust is this mechanism?

Mechanical sea ice-ocean interactions



Momentum advection	Coriolis force	External Stresses	Potential forces	Rheology

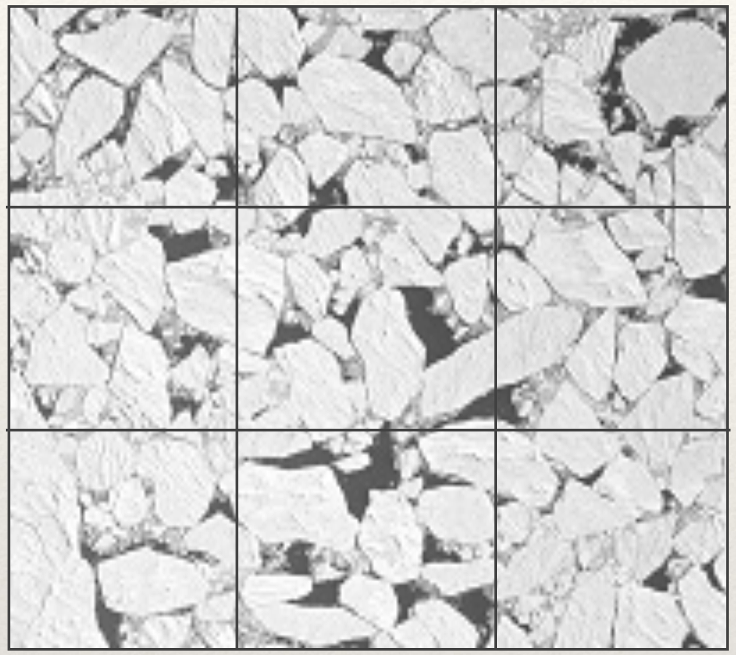
Ice
$$\frac{D\mathbf{u}_i}{Dt} = -f\mathbf{k} \times \mathbf{u}_i + m_i^{-1}\boldsymbol{\tau} - \nabla\phi(0) + m_i^{-1}\nabla\cdot\boldsymbol{\sigma}$$

Ocean
$$\frac{D\mathbf{u}_o}{Dt} = -f\mathbf{k} \times \mathbf{u}_o - m_o^{-1}\boldsymbol{\tau} - \nabla\phi(0) + \nu\nabla^2\mathbf{u}_o$$

Ocean-ice drag: $\boldsymbol{\tau} = c\rho_0 C_d(\mathbf{u_o} - \mathbf{u_i})|\mathbf{u}_o - \mathbf{u}_i|$

Sea ice rheology: e.g. visco-plastic shear-thinning fluid **(Hibler III,1979)**

Mechanical sea ice-ocean interactions



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$$\downarrow$$

$$\nabla\cdot\sigma \sim m_i f(u_i - u_o) \sim \tau$$

$$f\mathbf{k}\times\mathbf{u}_o \approx -\nabla\phi(0)$$

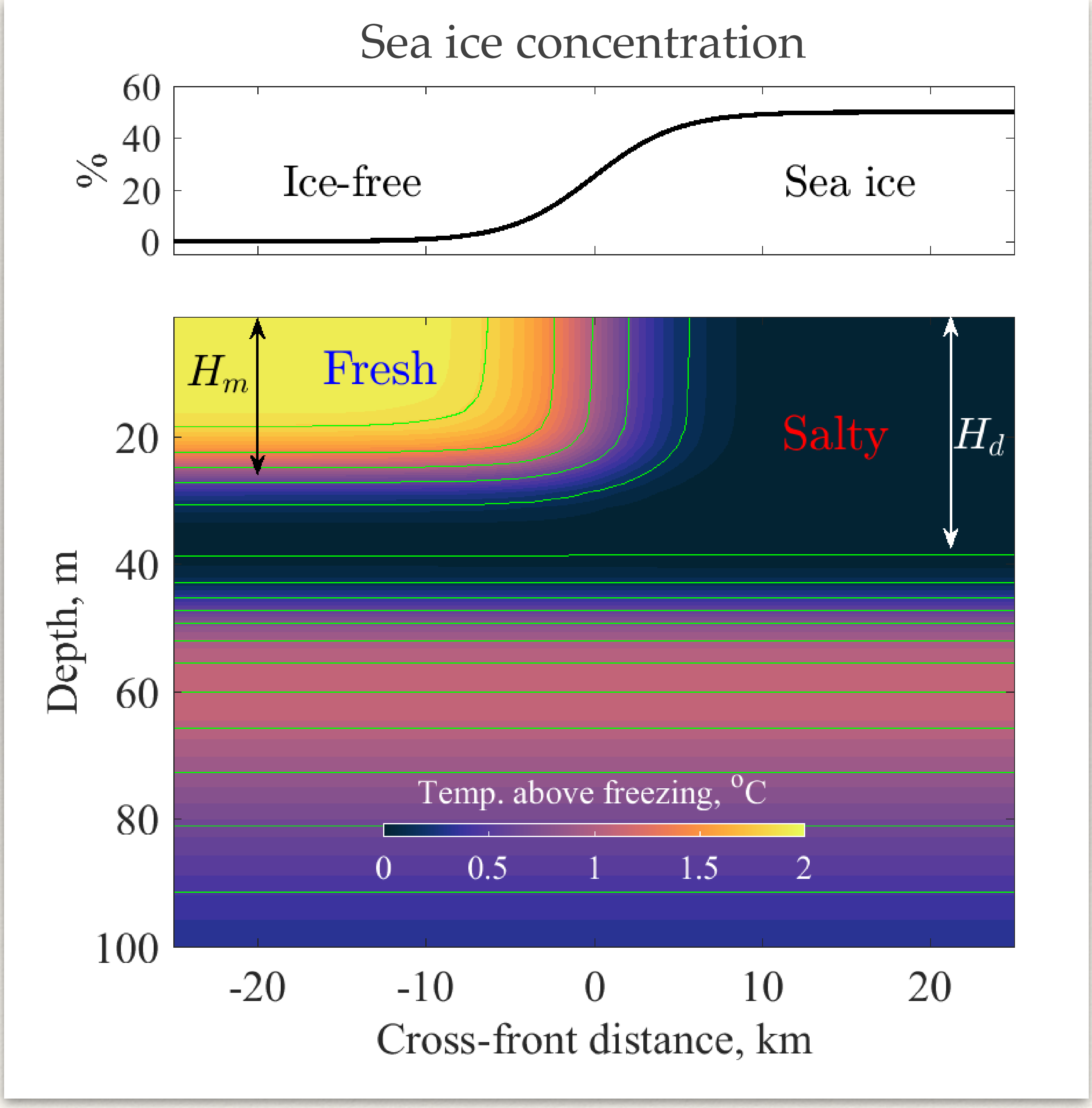
$$\rightarrow \quad \frac{\zeta_i - \zeta_o}{\zeta_o} \sim \frac{m_i}{R_d\ Ro\ C_d} \sim O(0.1)$$

in MIZs

Manucharyan & Thompson (2017)

Sufficiently low-concentrated sea ice over submesoscale eddies
must mimic the upper-ocean vorticity!

Simulations of ice-covered mixed layer instabilities



Hypothesis: instabilities of meltwater fronts in MIZs can strongly affect sea ice dynamics

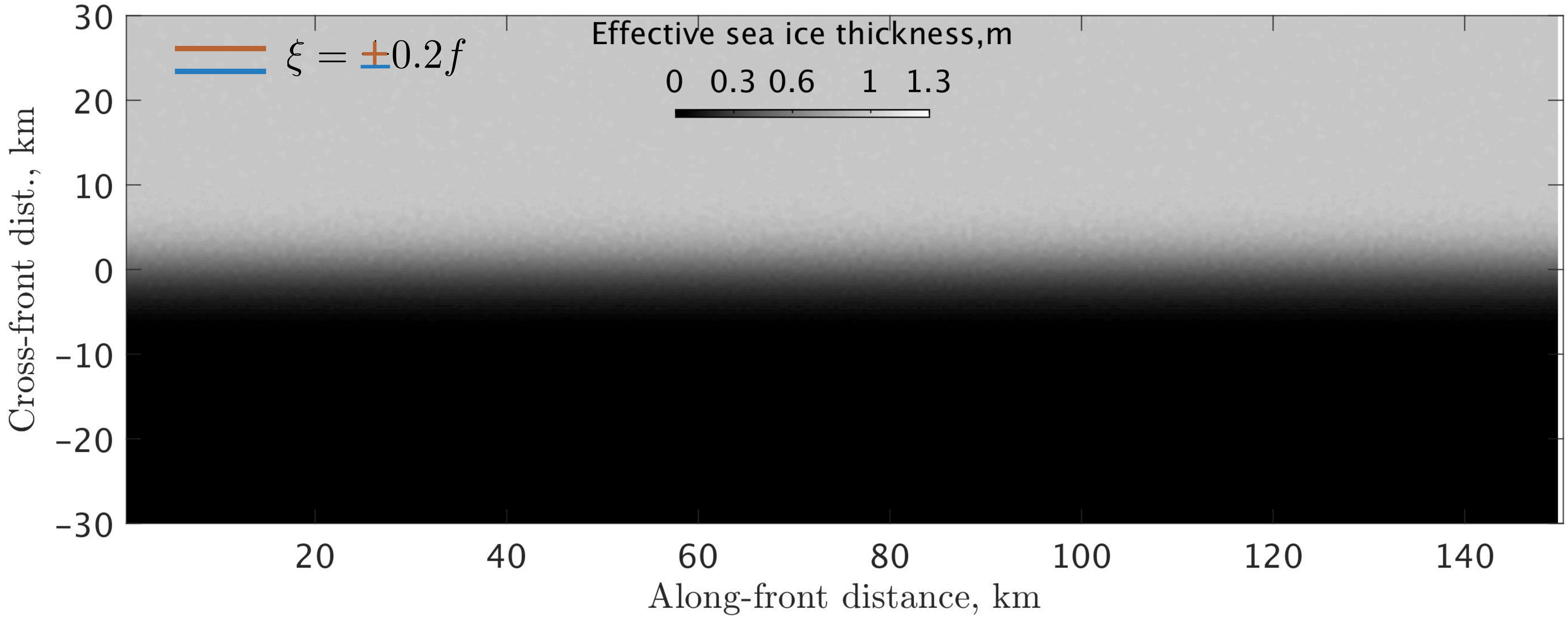
- **MITGCM:** simulations of sea ice dynamics (as a visa-plastic fluid) over an eddying mixed layer.

  Initial frontal conditions are idealizations of the observed fronts.

  Grid of 0.5 km allows the development of frontal instabilities and ice-ocean stresses that redistribute sea ice

Simulations of ice-covered mixed layer instabilities

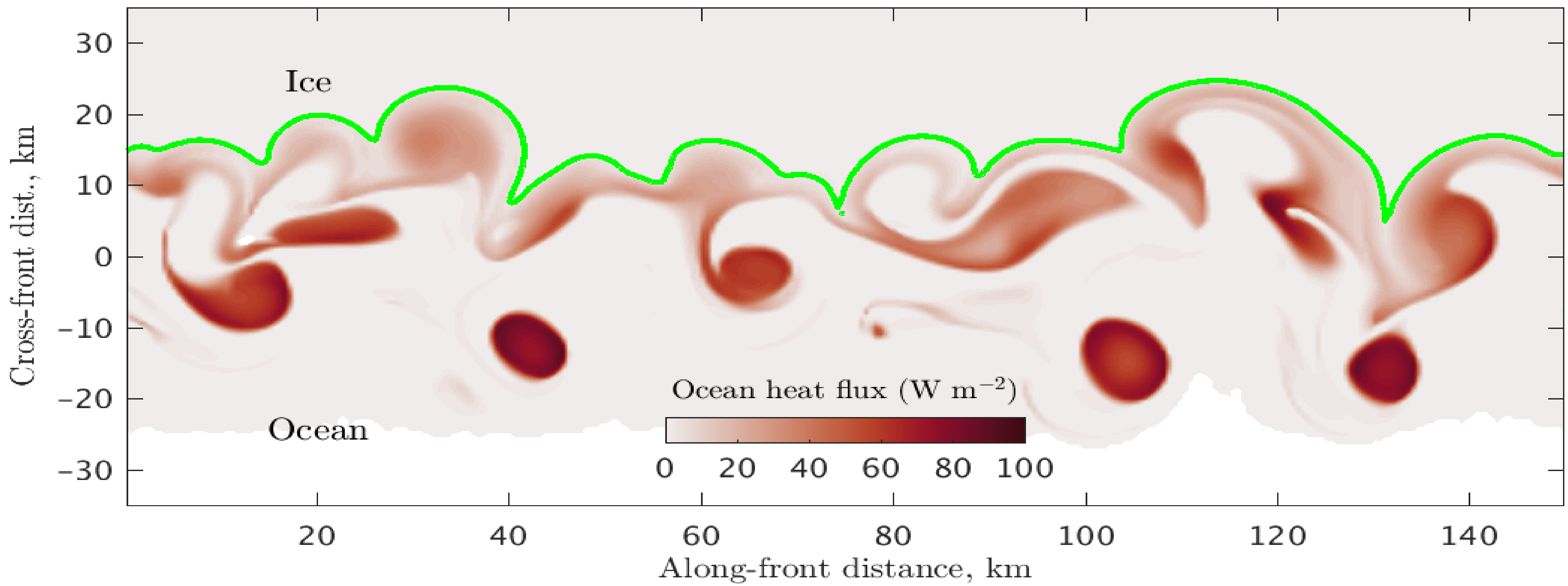
Manucharyan & Thompson (2017)



- Marginal ice zone **expands** due to an intense **lateral sea ice transport.** Sea ice is not a passive tracer.
- **Cyclonic** eddies (~10km, 0.2 m s^{-1}) **accumulate** the sea ice while **anticyclones repel** it.
- **Vertical** velocities are **O(10 m day^{-1})** and ice-ocean heat fluxes reach **O(100 W m^{-2})!**

Enhanced sea ice-ocean **heat fluxes** in marginal ice zones

Manucharyan & Thompson (2017)



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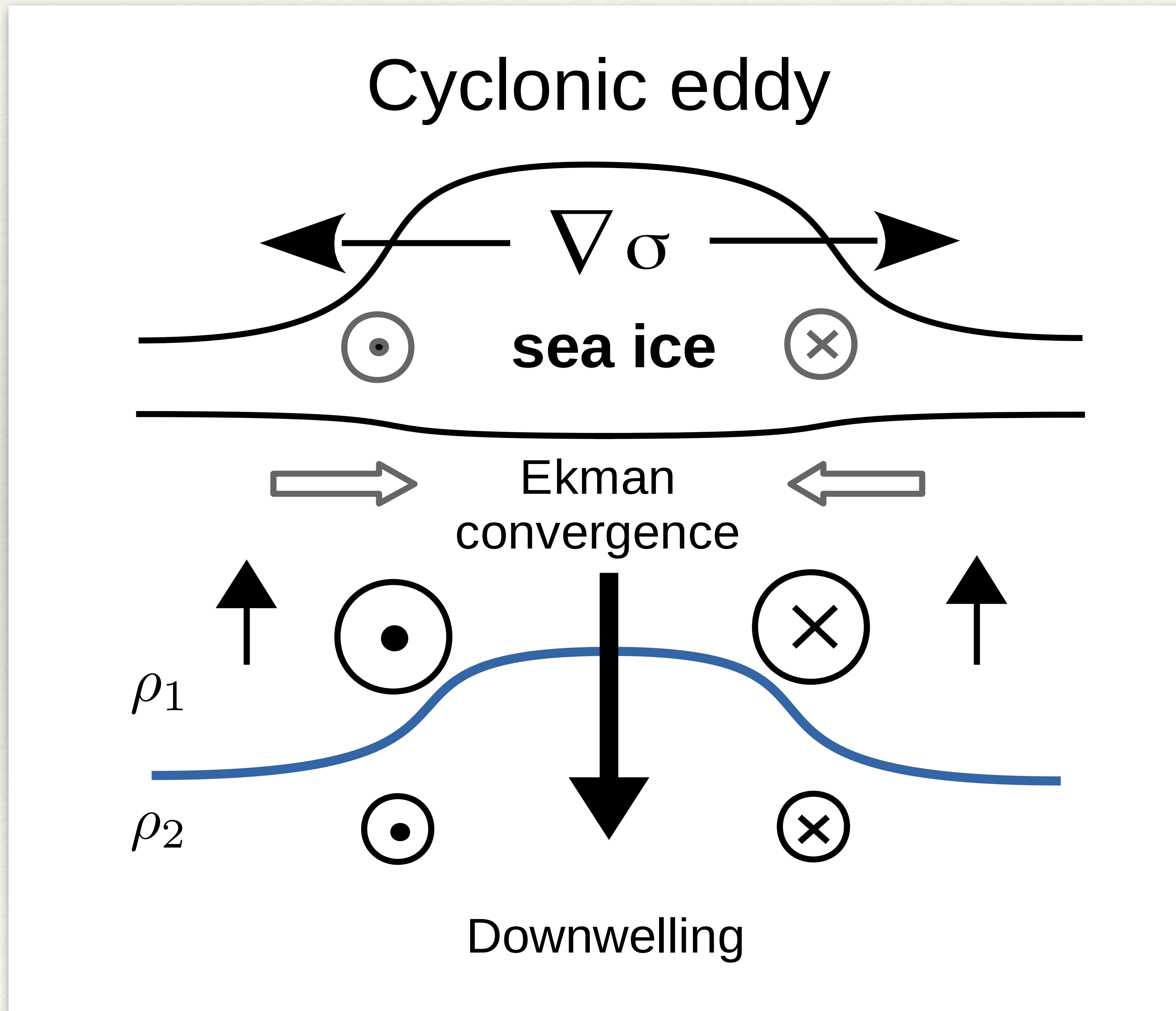
Sea ice accumulation in cyclonic eddies and filaments



Constitutive law: $P(c) = P_0 c^{\alpha}$

Mass conservation:

$$\partial_t c + \partial_y (v_i c) = 0$$

Force balance:

$$\rho C_d c(v_i - v_o) + h P_0 \partial_y c^{\alpha} = 0$$

$$\downarrow$$

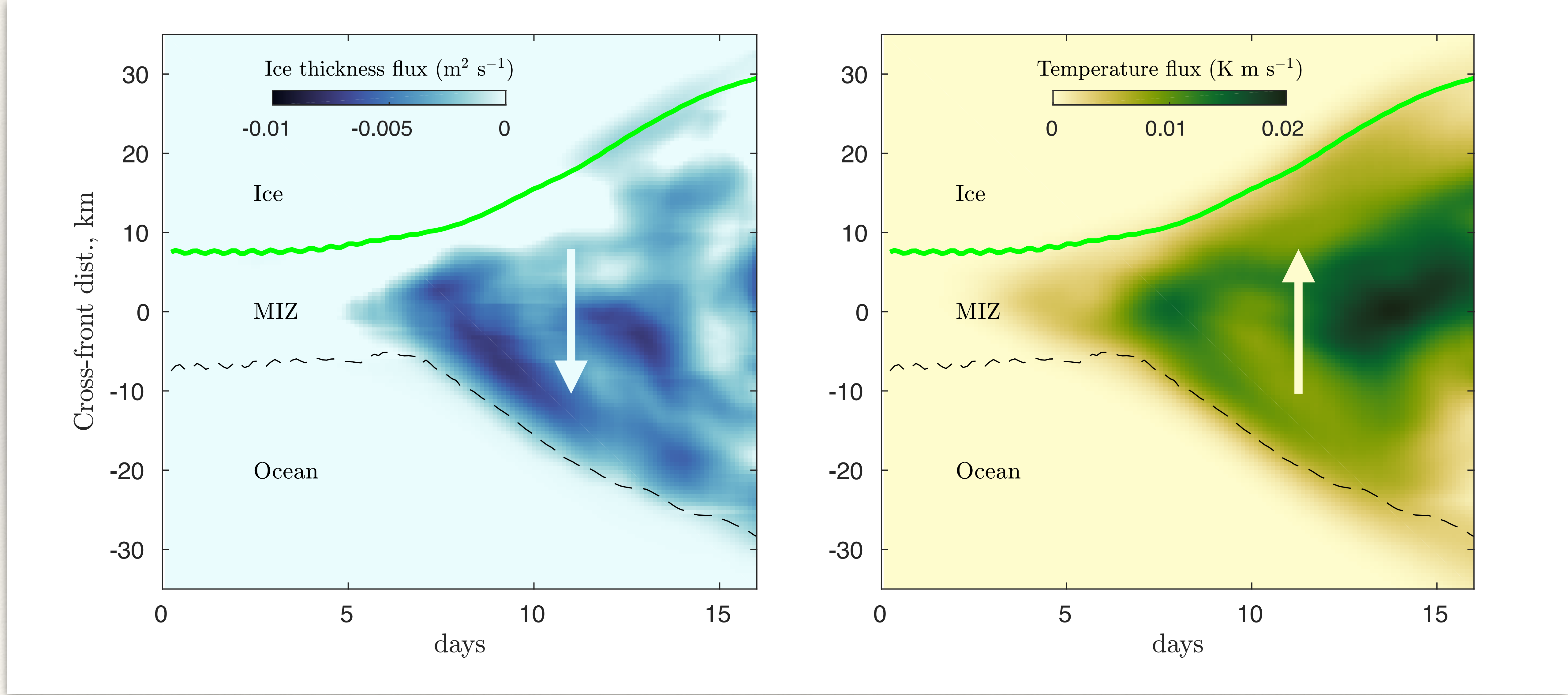
Non-linear adv.+diffusion:

$$\partial \hat{c}_t = -\partial_y [v_0(y)\hat{c} - \partial_y \hat{c}^{\alpha}]$$

Fajber et al (in prep.)

Lateral heat and sea ice transport across the MIZ

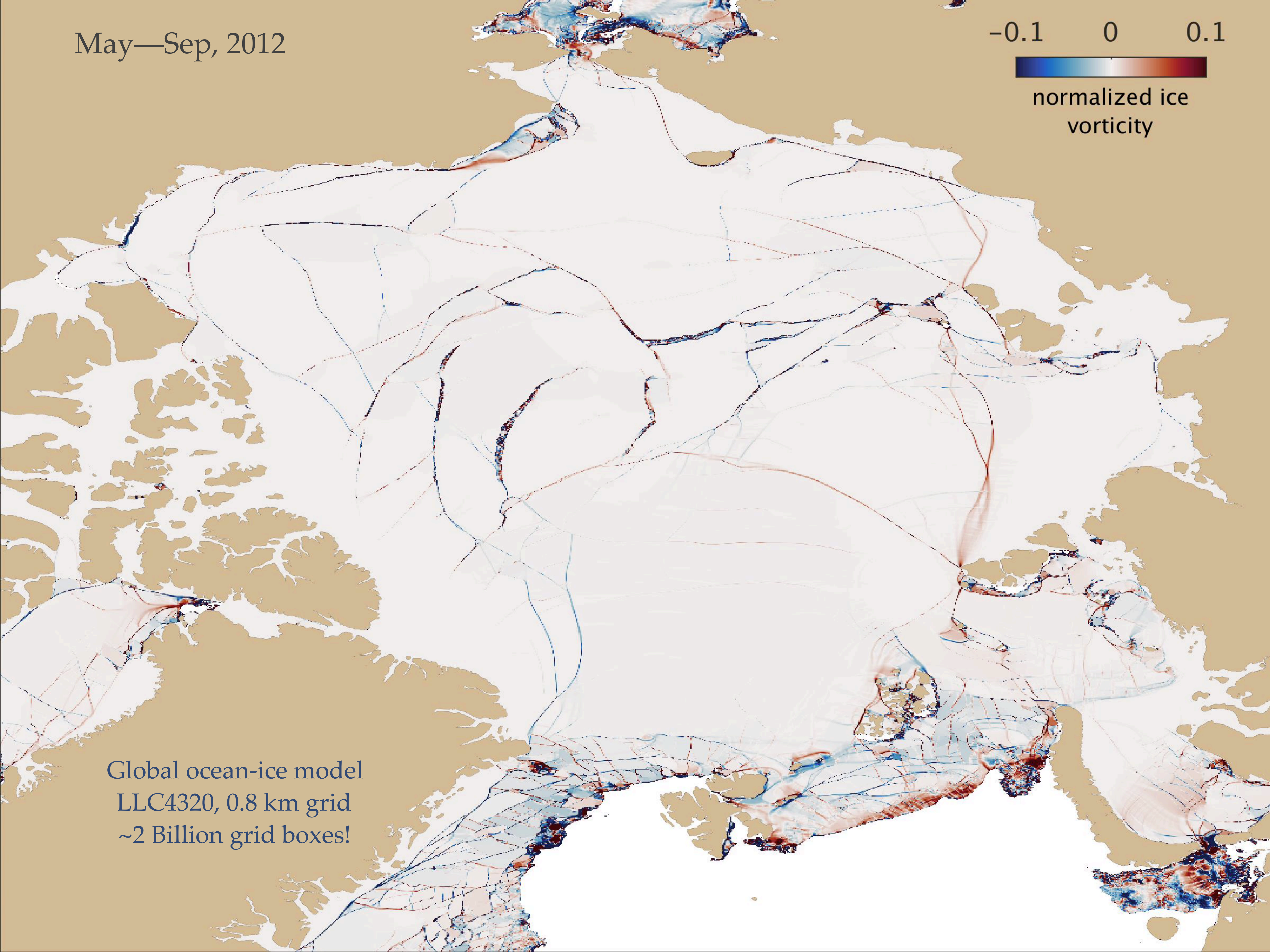
Ice volume transport: $< v'h'_{eff} >$ **Surface heat transport:** $< v'T' >$



Tracer diffusivity K=O(200m²/s); scales linearly with initial frontal Rossby number.

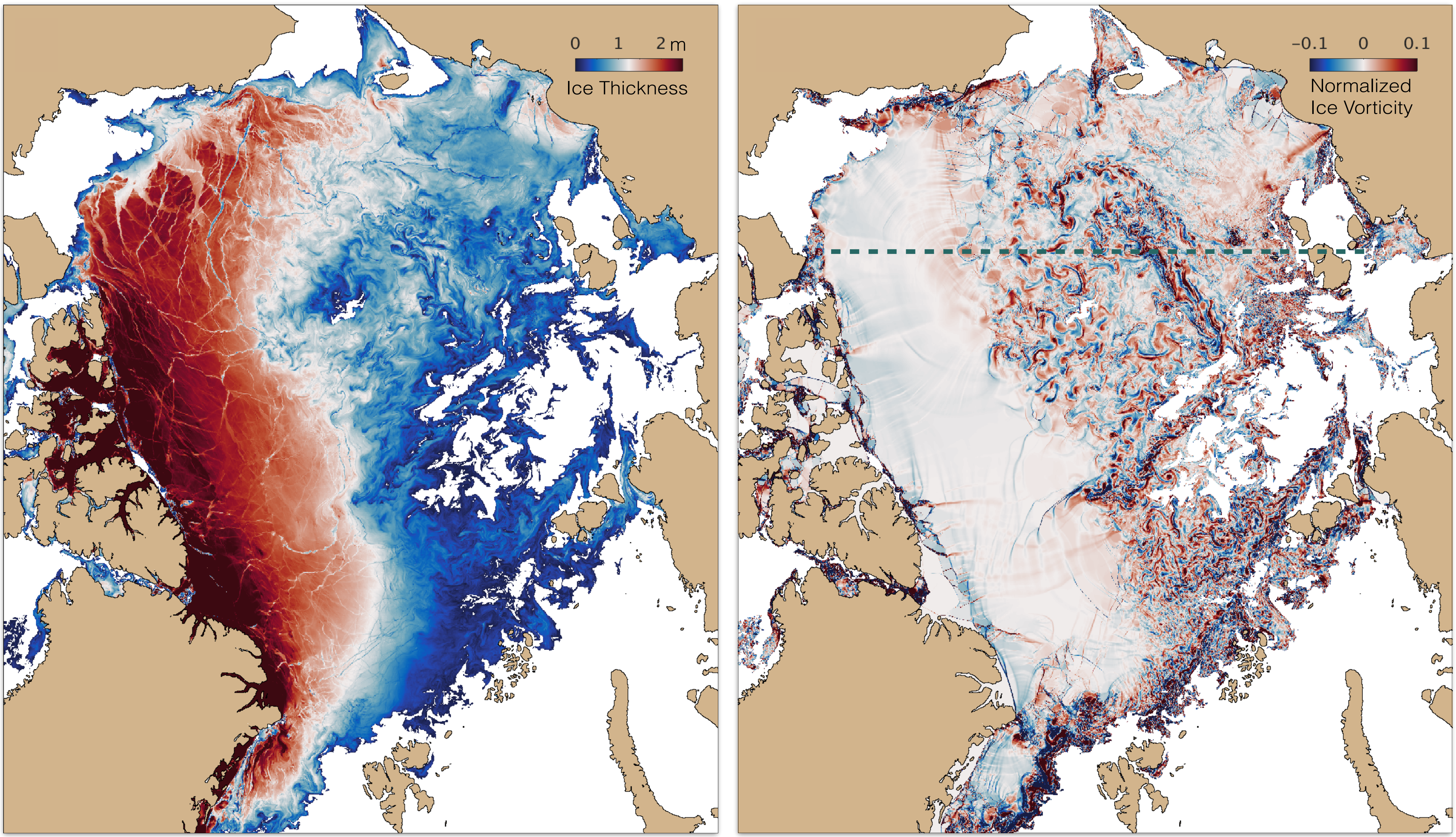
Part II. Arctic-wide influence of mesoscale and submesoscale ocean variability on sea ice

Is there a significant mesoscale/submesoscale variability in the Arctic? How does it affect the sea ice dynamics?



May—Sep, 2012
-0.1
0
0.1
normalized ice vorticity
Global ocean-ice model
LLC4320, 0.8 km grid
~2 Billion grid boxes!

Thickness {sea ice} Vorticity



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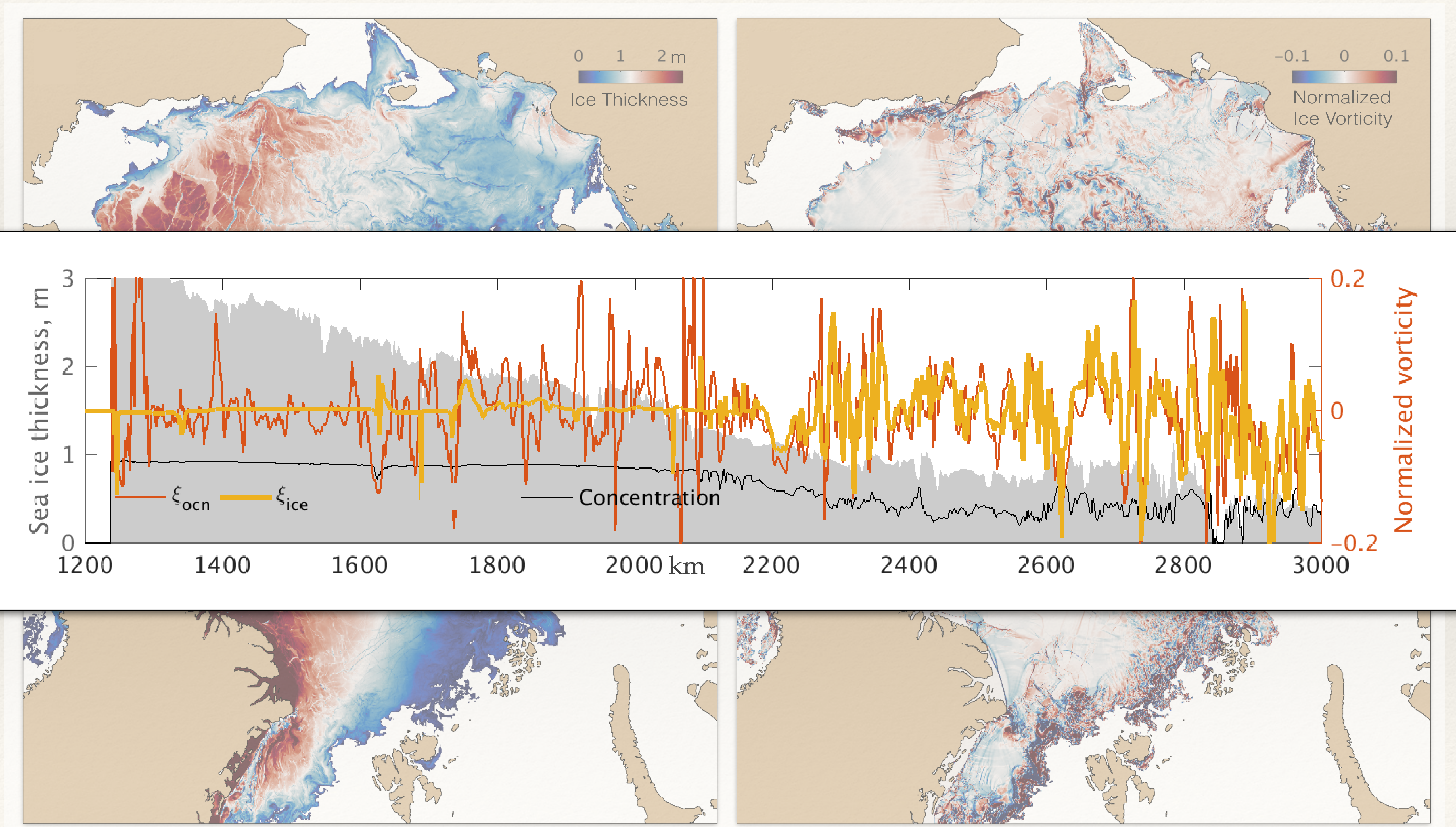
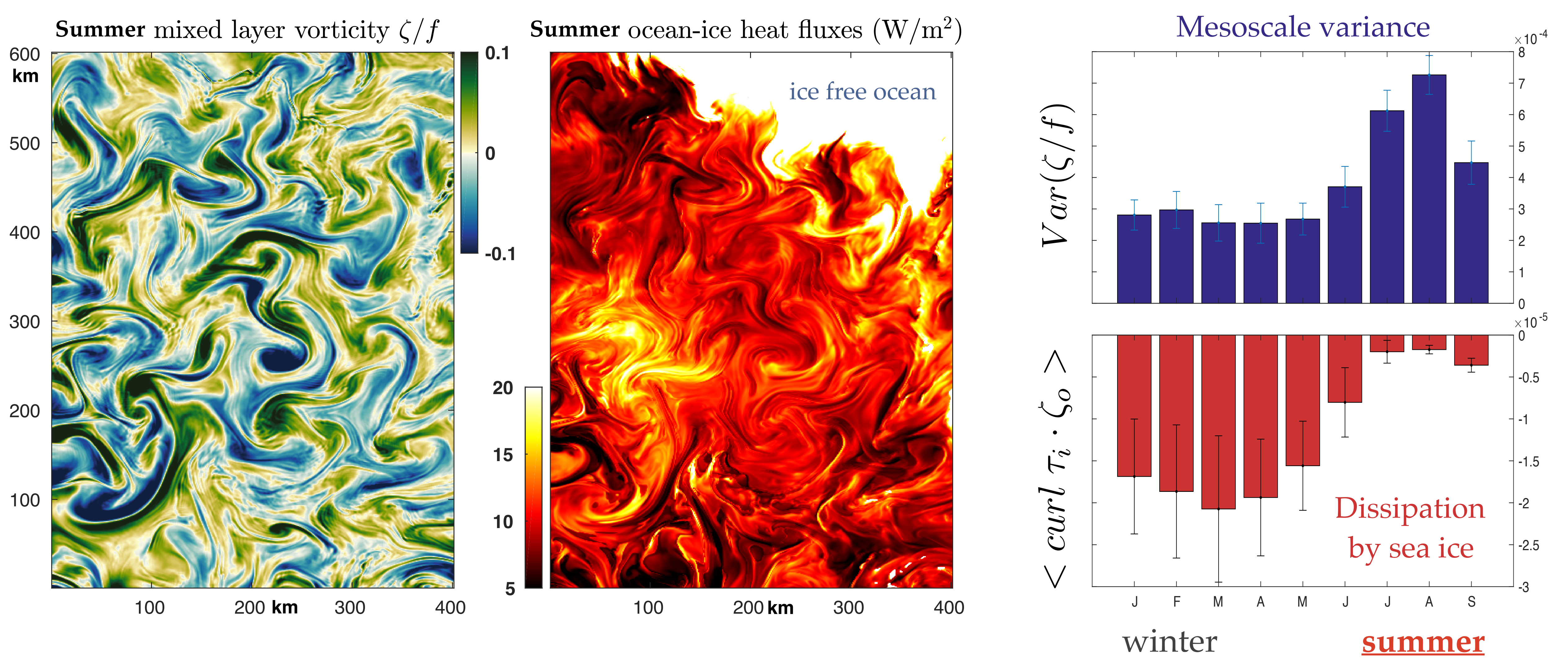
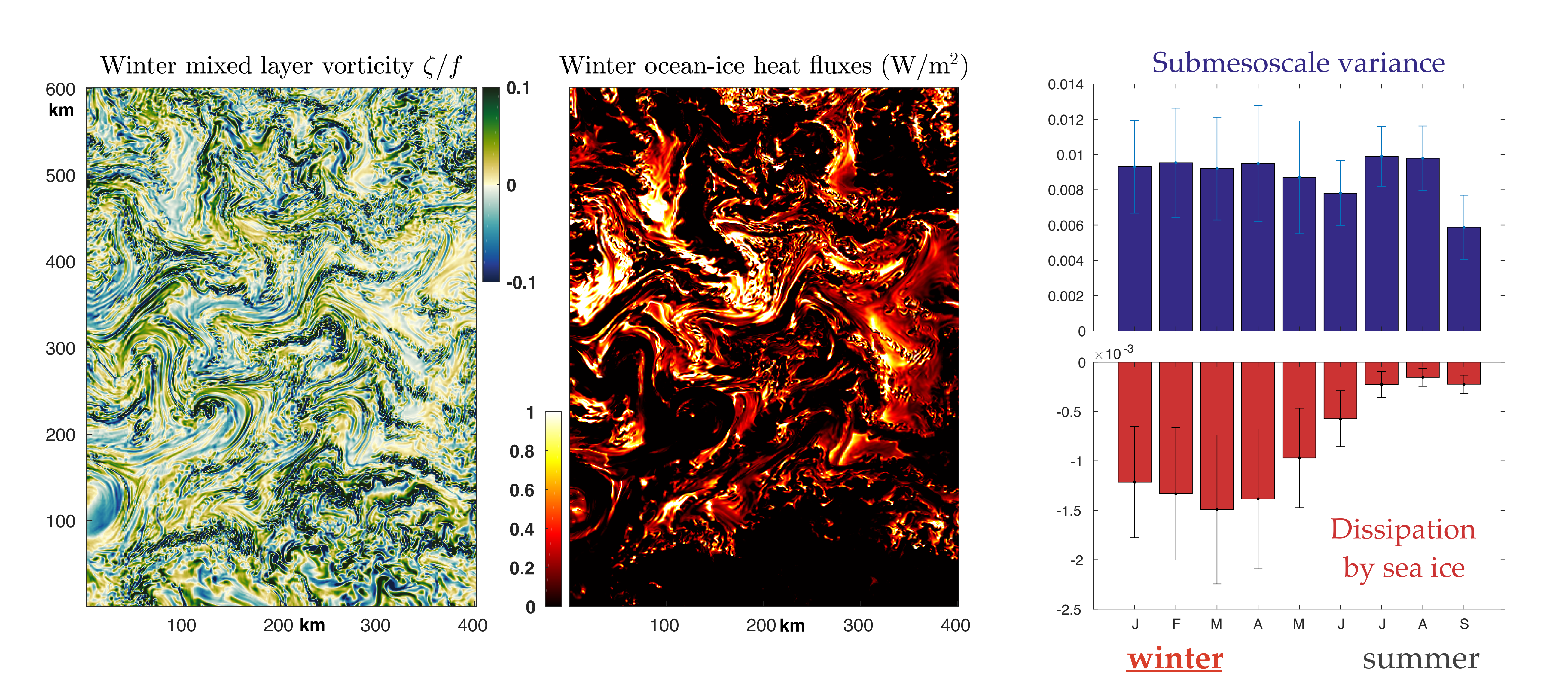


Eddy-enhanced ocean-ice heat fluxes: **summer**



Surface expression of mesoscale eddies is strongest in the summer when dissipation by sea ice is minimized. Ocean-ice heat flux is a stirred field!

Eddy-enhanced ocean-ice heat fluxes: **winter**



Despite low Ro~0.2, winter-time submesoscale activity constitutes about 80% of the average 2.4 W/m² ocean-ice heat fluxes Arctic-wide.

Summary of sea ice-ocean interactions

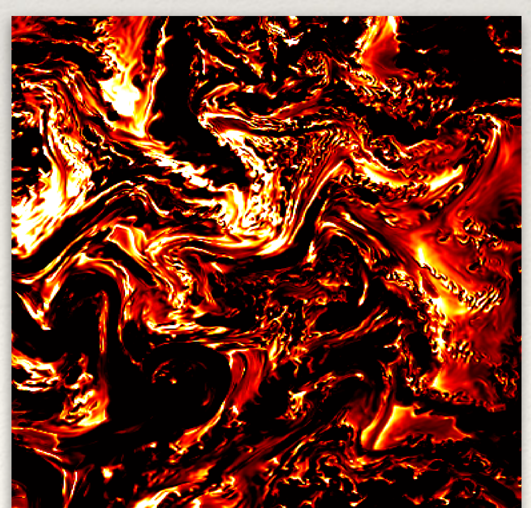
MLI is prominent in MIZs, strongest frontogenesis occurs in summer and convective instabilities in winter.

Sea ice gets trapped in cyclones and gains its vorticity, dramatically **decreasing** the upper-ocean **dissipation**.

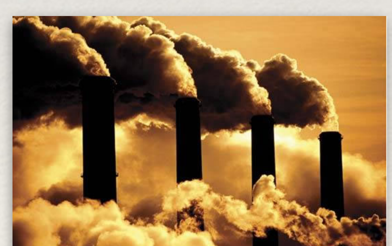
Sea ice dynamics is getting more '**turbulent**' because of **weaker** eddy **dissipation** in the upper ocean.

Increased **eddy energy** may contribute to the **enhanced** ocean **heat fluxes** and accelerated **sea ice melt.**

Sea ice melt

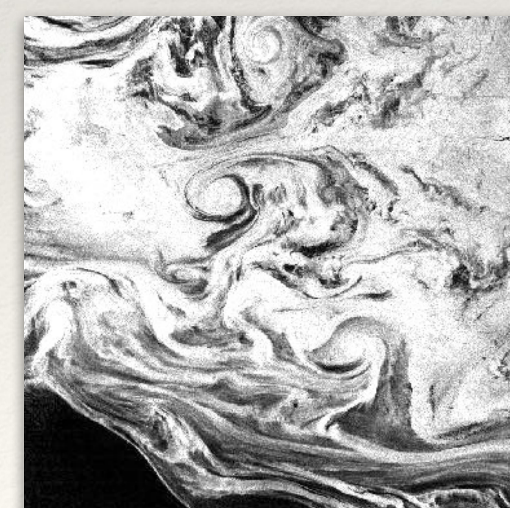


Enhanced vertical heat fluxes



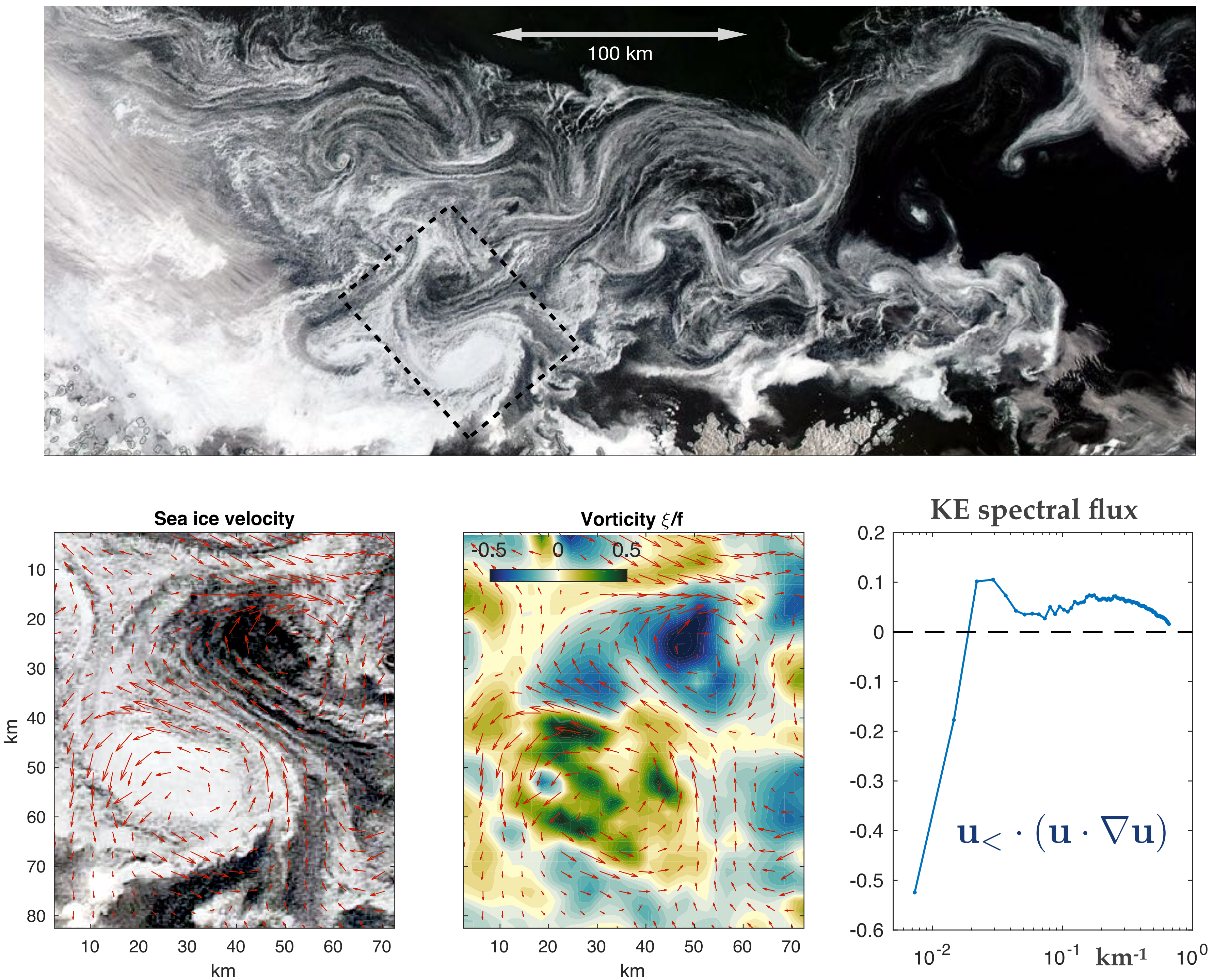
Global Warming

Enhanced upper-ocean variability



More goods?

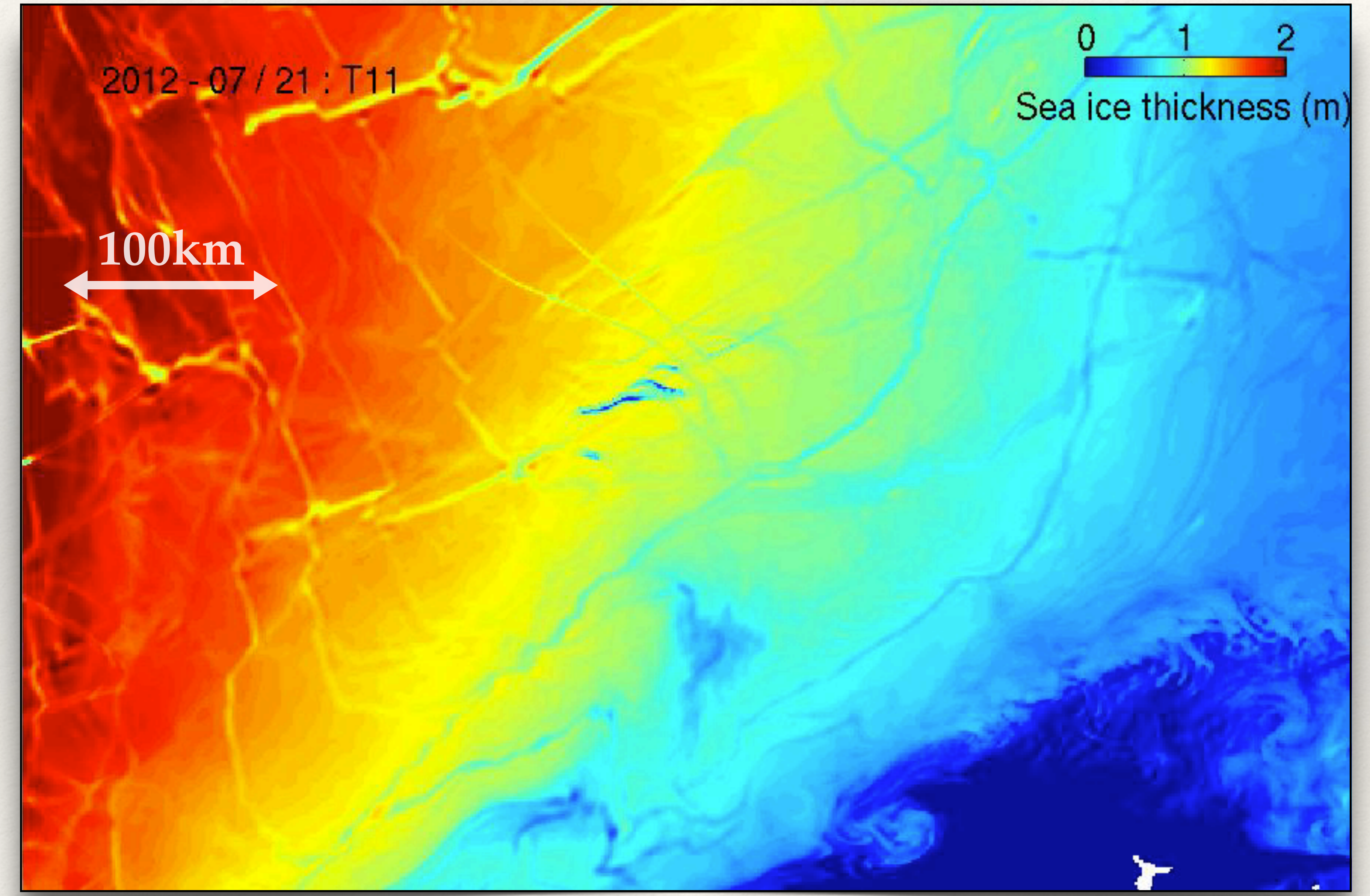
Seeing the ocean through sea ice



$$u_o = F(u_i, \sigma) \ ?$$

- What is the relation between sea ice and ocean velocities?
- Under which atmospheric conditions the ocean vorticity field is reflected in sea ice concentrations?
- What can we learn about submesoscale ocean dynamics from sea ice observations?

Addressing scale interactions in sea ice dynamics: eddies, internal waves, and mixing hotspots



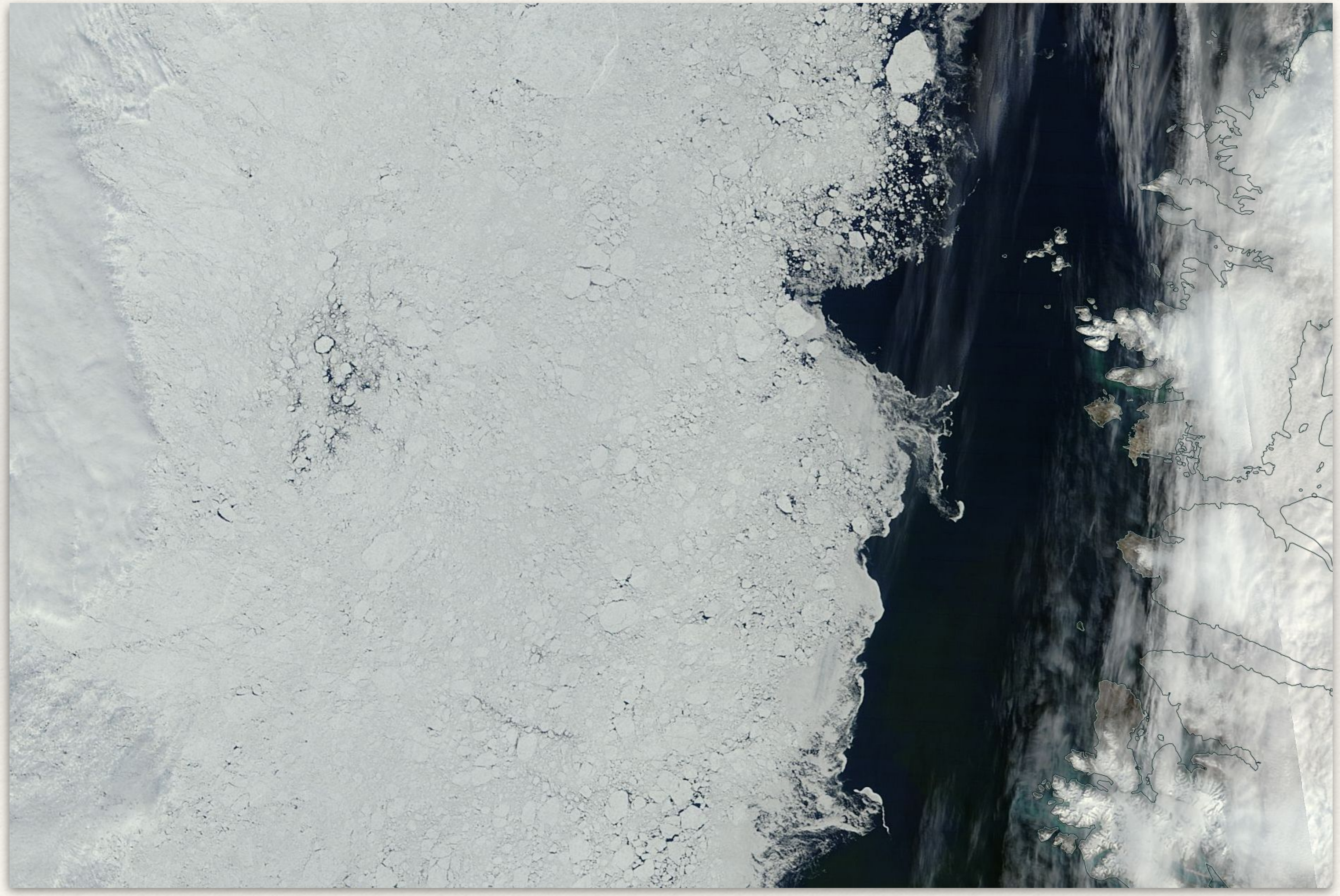
Sea ice dynamics North of Svalbard (MITGCM, ~1km res.)

Internal waves break up the sea ice exposing it the open ocean to atmospheric fluxes

Mixing hotspots in Arctic Ocean affect halocline thickness and vertical heating

Eddies and waves become more energetic because of the changing damping

Addressing scale interactions in sea ice dynamics: eddies, internal waves, and mixing hotspots



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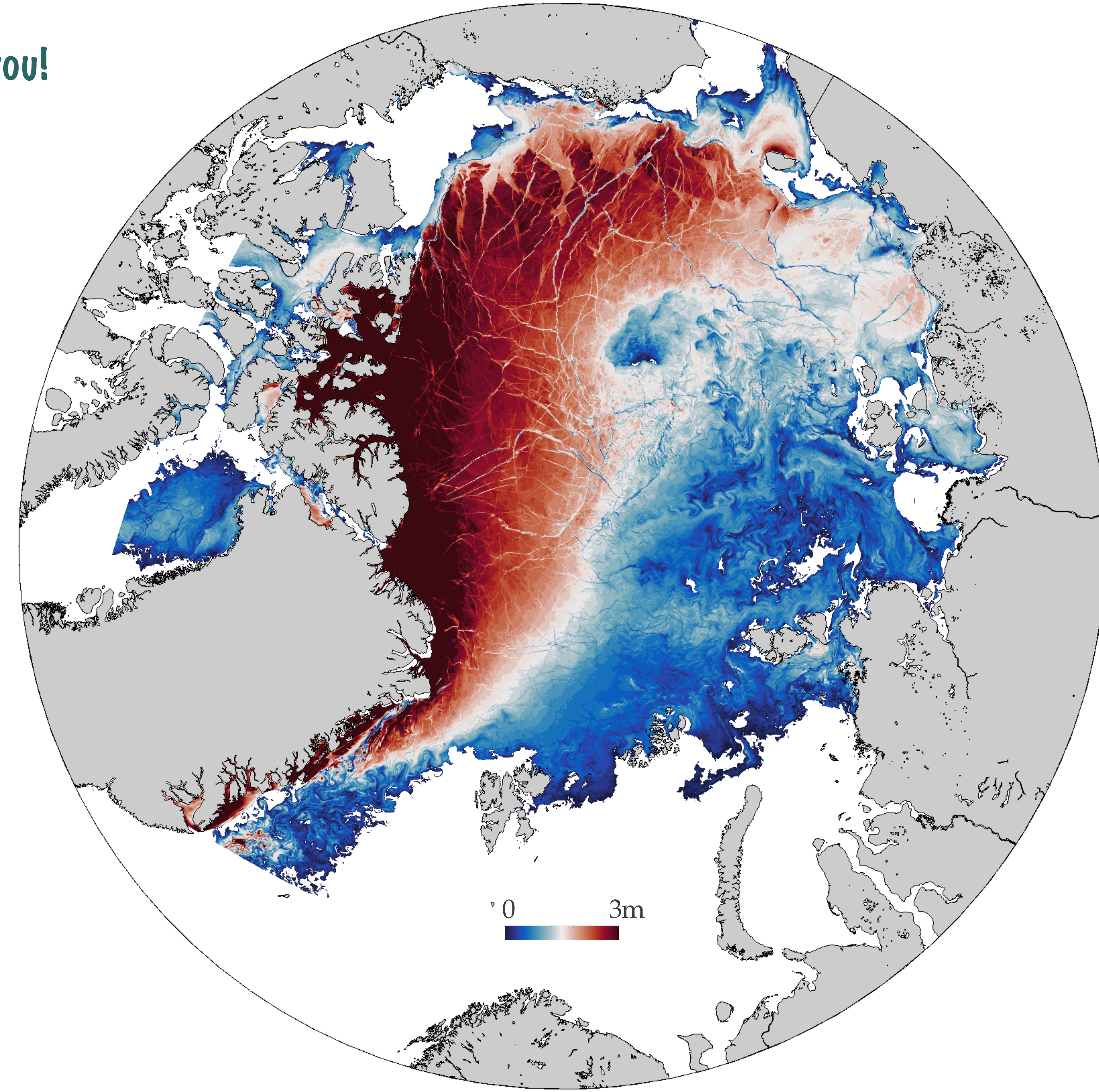
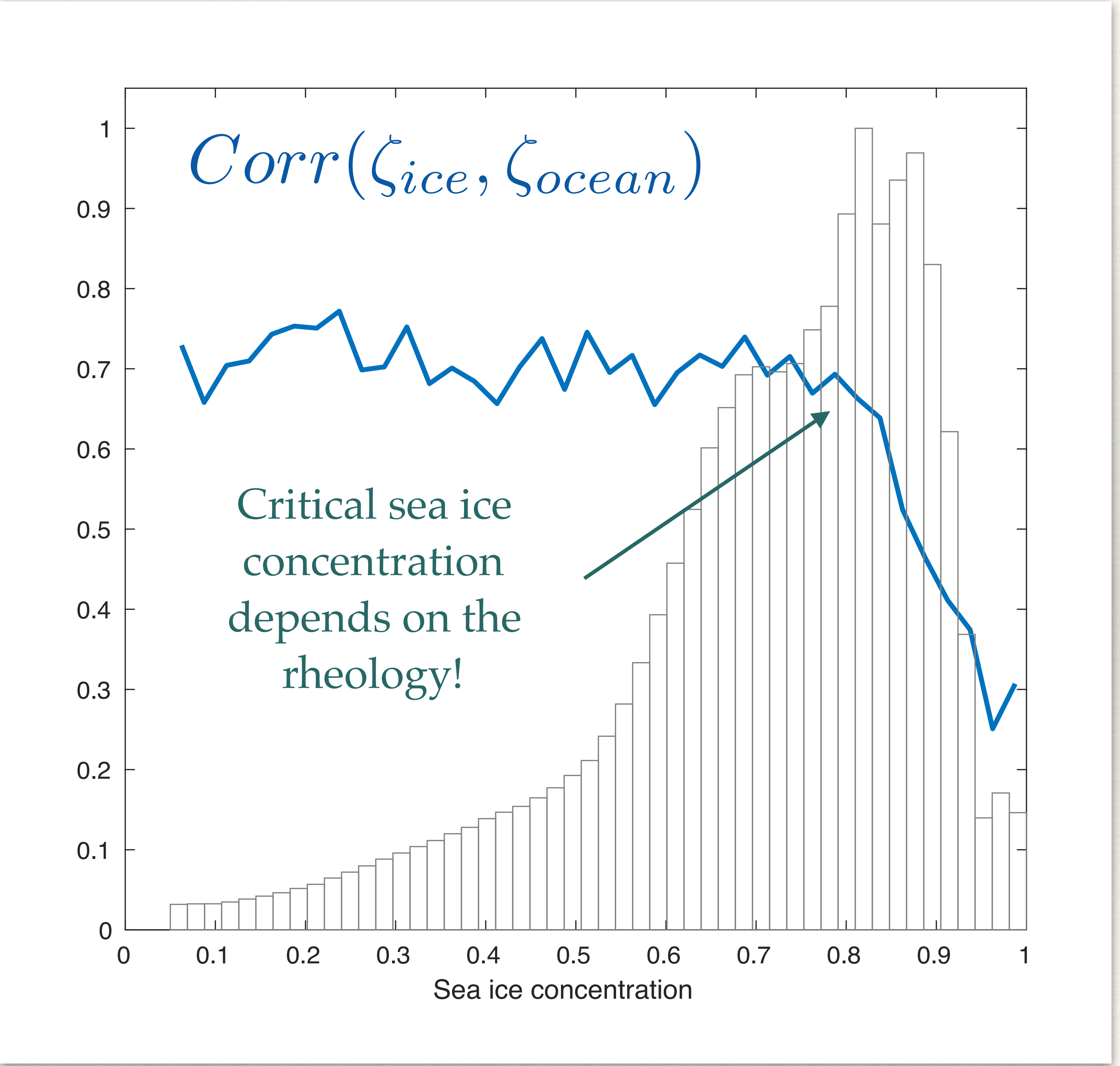
Thank you!



Questions?

Critical influence of sea ice on upper-ocean vorticity



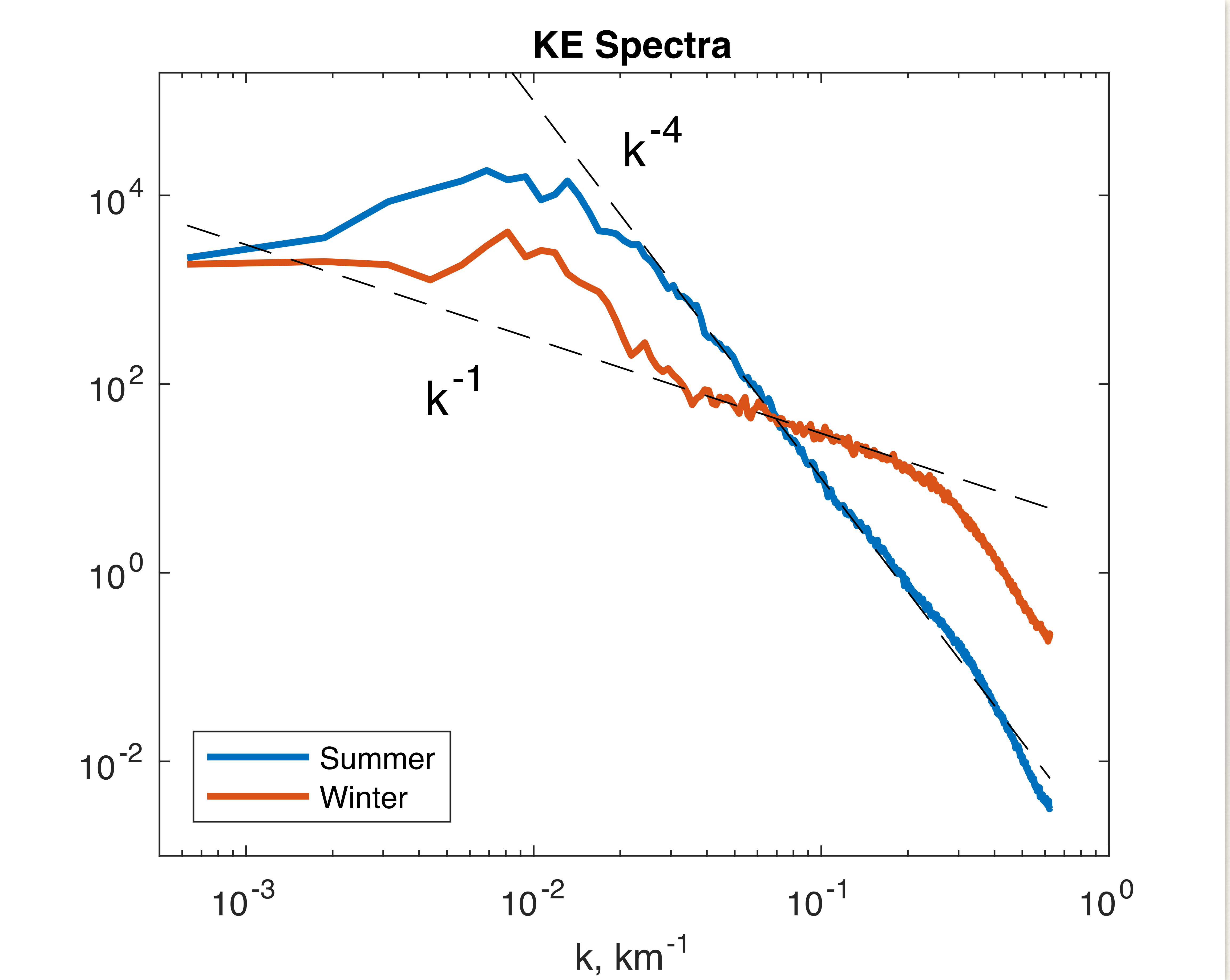
Ekman eddy spindown

$$\nabla \times \tau_i \sim (\zeta_i - \zeta_o)$$

Vorticity dissipation by ice

$$[\zeta_o^2]_t \sim (\zeta_i - \zeta_o)\zeta_o + S$$

Correlation between the ice and ocean vorticity occurs when c<80% and significantly **reduces** upper- ocean **dissipation**



KE Spectra
k^-4
k^-1
10^4
10^2
10^0
10^-2
10^-3
10^-2
10^-1
10^0
k, km^-1
Summer
Winter

Enhanced heat fluxes over anticyclones