Eddies and Linear Kinematic Features: Do they shape the Sea-Ice Growth and sea-ice ocean dynamics in the Arctic?

Laboratoire d'Océanographie Physique et Spatiale, IFREMER/CNRS

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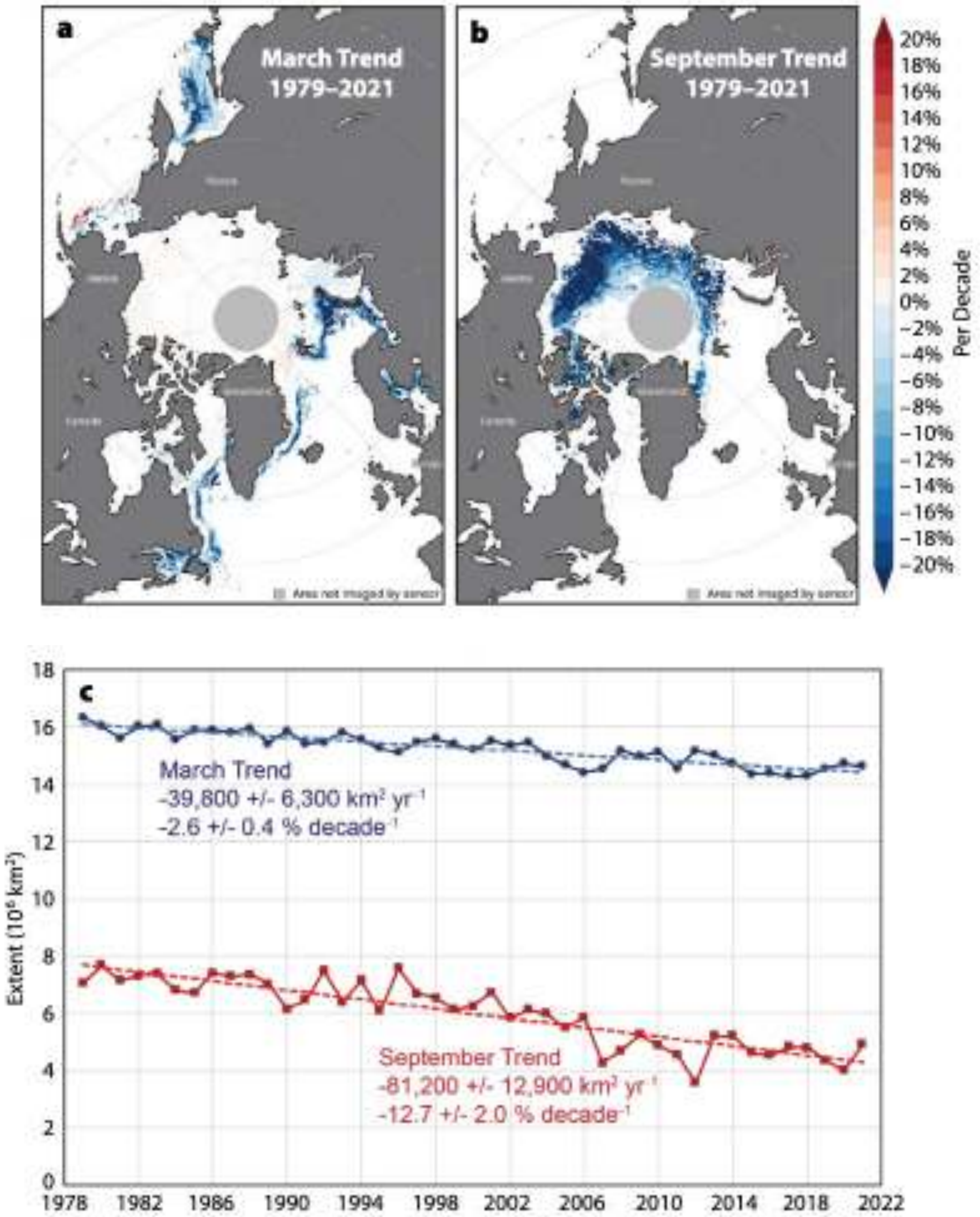
NOC 22-June-2023

Background

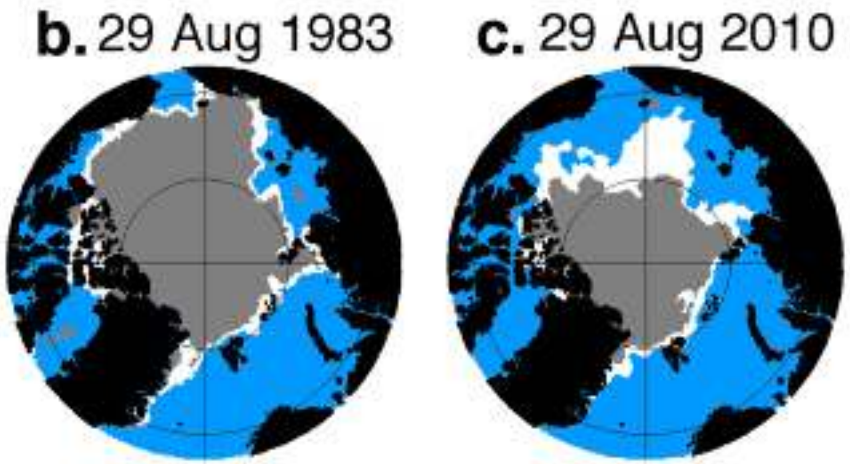
- Ice **decreasing** trend, that will amplify in the future
  - *Overall a response to our anthropogenic CO_2 emissions*



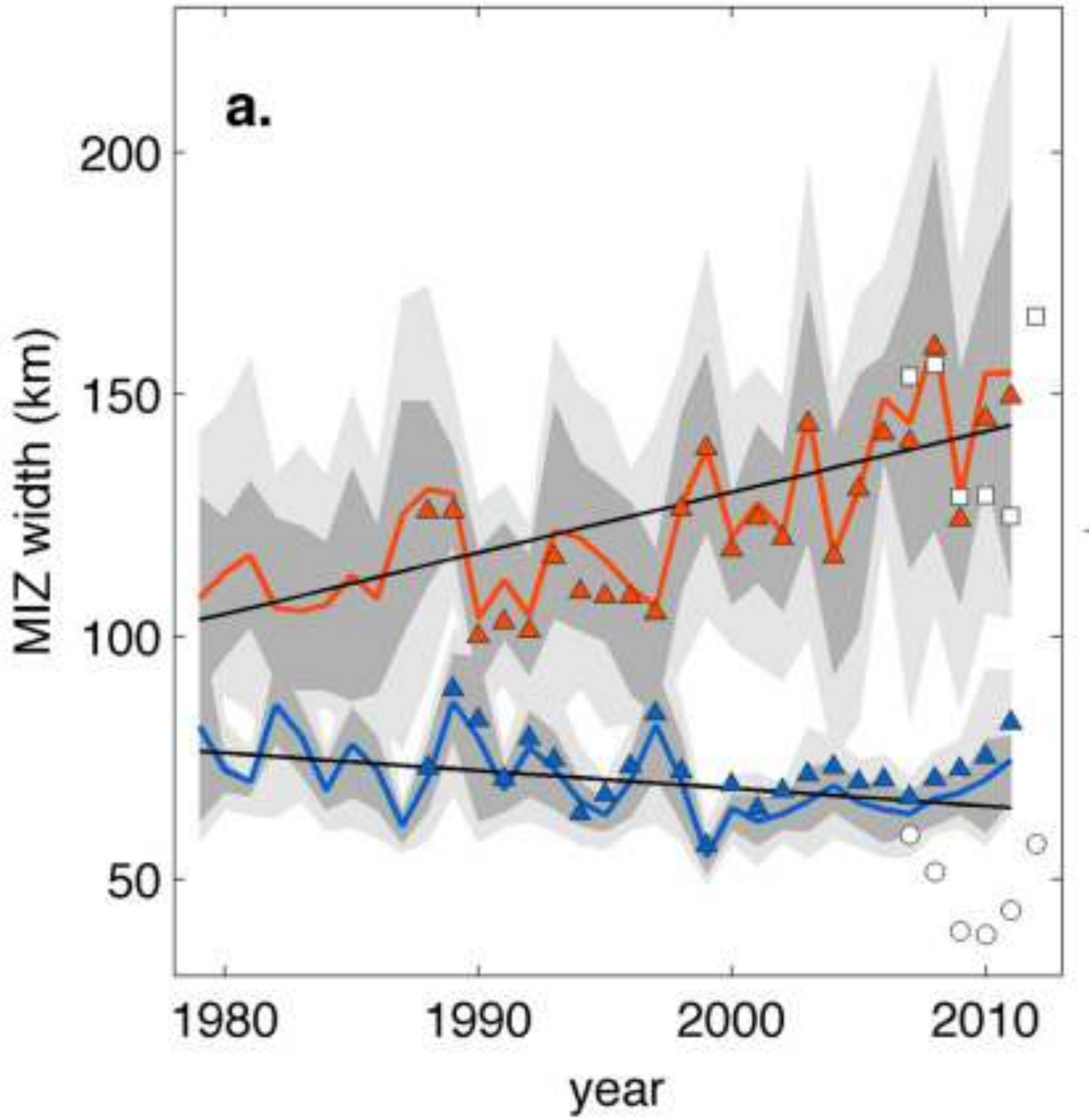
Meier, W., Center, N. S. and I. D. & Stroeve, J. An Updated Assessment of the Changing Arctic Sea Ice Cover. *Oceanography* (2022) doi:10.5670/oceanog.2022.114.

Background

- Marginal ice zones summer width has increased.
  - Likely increase the effect of the oceanic eddy field into the sea-ice



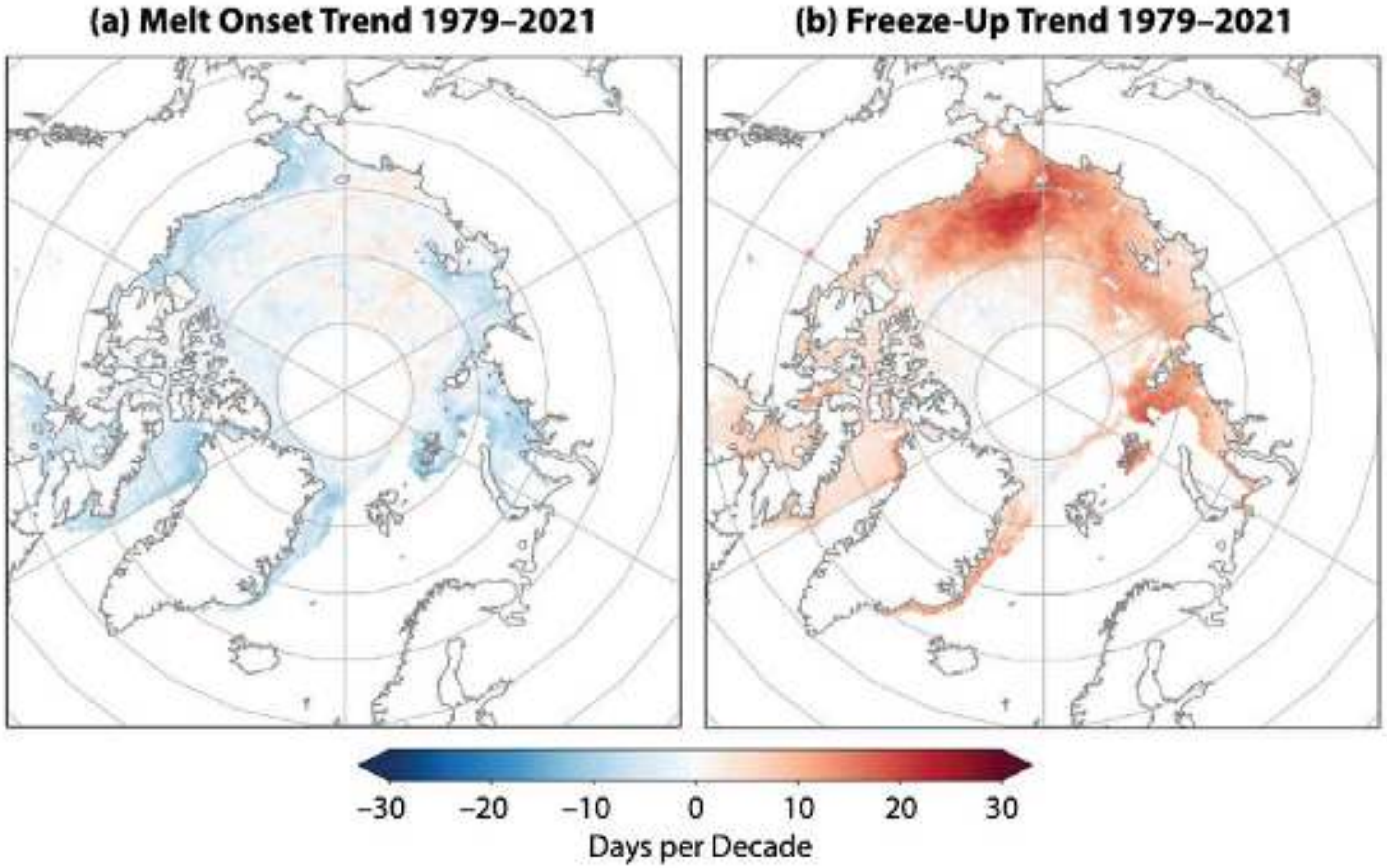
White = Marginal Ice Zone
Gray = Ice Pack



Strong, C. & Rigor, I. G. Arctic marginal ice zone trending wider in summer and narrower in winter. *Geophys Res Lett* **40**, 4864–4868 (2013).

Background

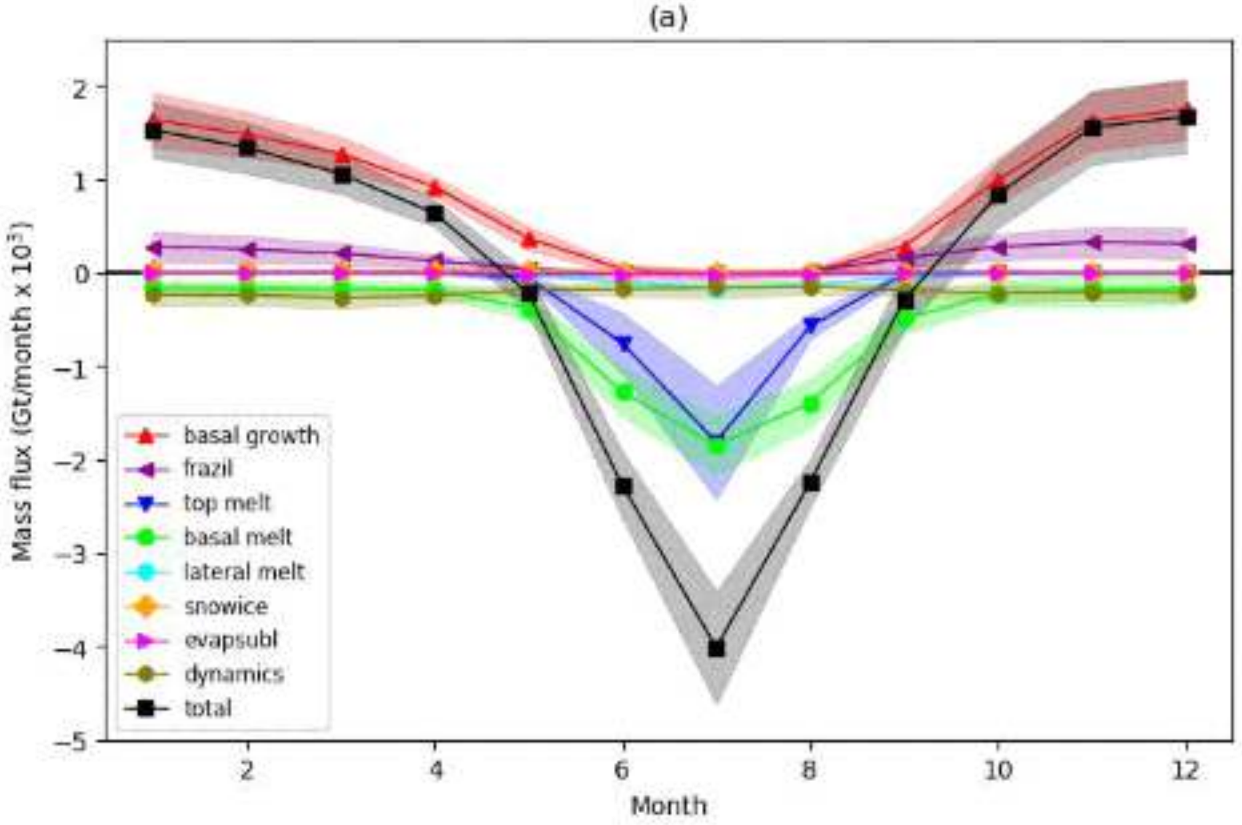
- Sea ice exhibits a large seasonality
  - Sea ice **melting** 🥵 is occurring earlier
  - Sea ice **freezing** 🥶 is occurring later



Meier, W., Center, N. S. and I. D. & Stroeve, J. An Updated Assessment of the Changing Arctic Sea Ice Cover. *Oceanography* (2022) doi:10.5670/oceanog.2022.114.

Background

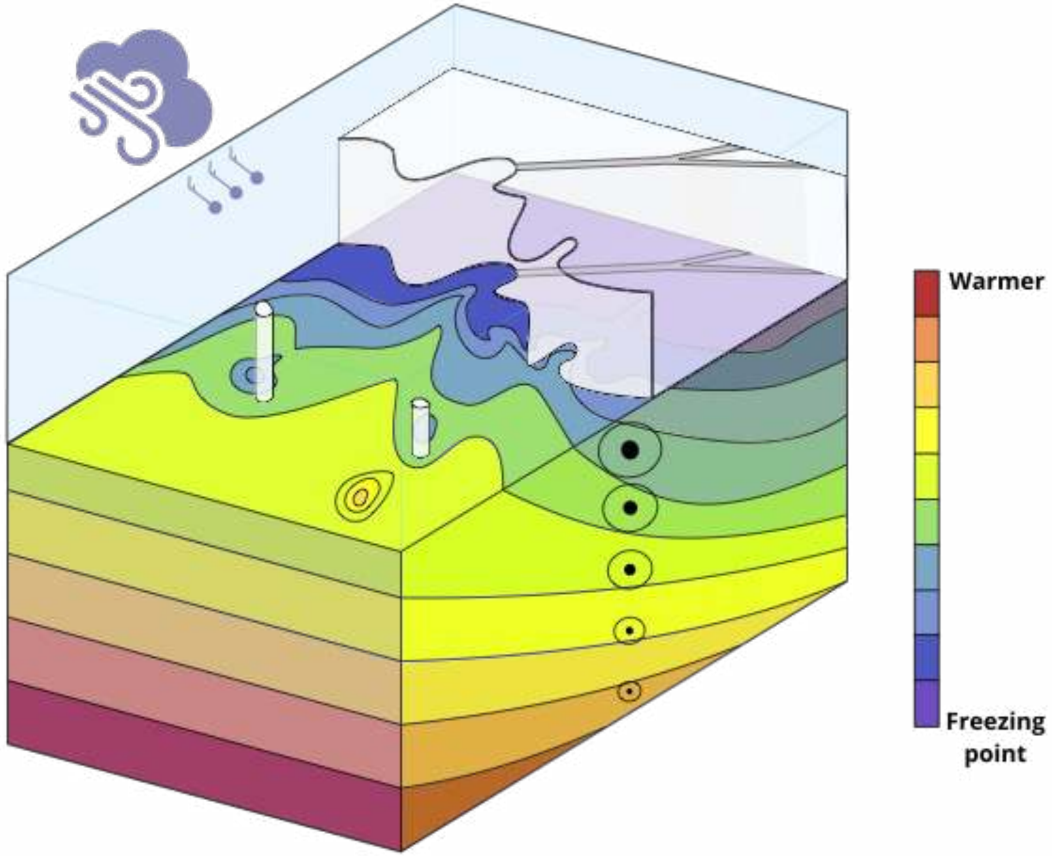
- Sea ice exhibits a large seasonality
  - Largely driven by thermodynamics
  - Ocean and Atmosphere drive ~50% of the melt (CMIP6 models)



Keen, A. *et al.* An inter-comparison of the mass budget of the Arctic sea ice in CMIP6 models. *The Cryosphere* **15**, 951–982 (2020).

Sources of heterogeneity in sea-ice

- Atmospheric heterogeneity
  - Air temperature
  - Precipitation
  - Snow
- Sea-ice advection
  - Winds (i.e. **LKF**)
  - Currents
  - Waves
- Ocean heterogeneity
  - **Mesoscale Eddies**
  - Submesoscale Eddies



SEDNA

Ocean Model

NEMO 4.0.5
1/60° Resolution
Pan-Arctic
150 vertical levels
7 year long experiment

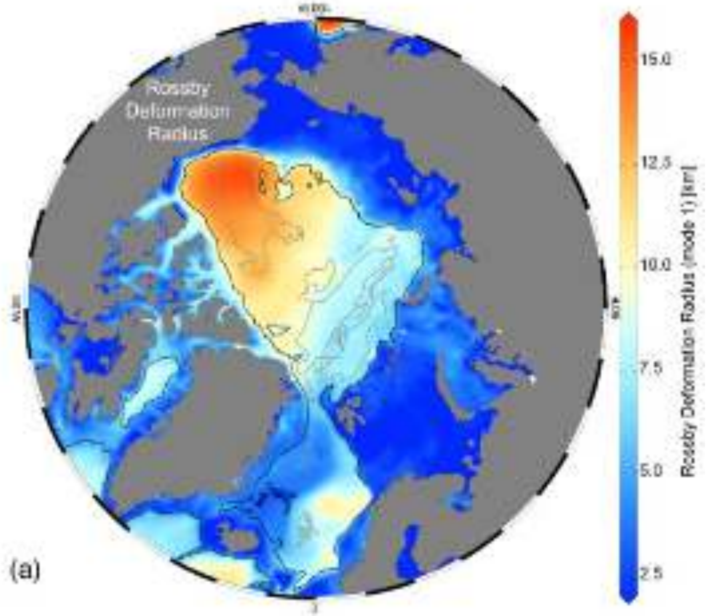
Talandier & Lique 2023

Sea-Ice Model

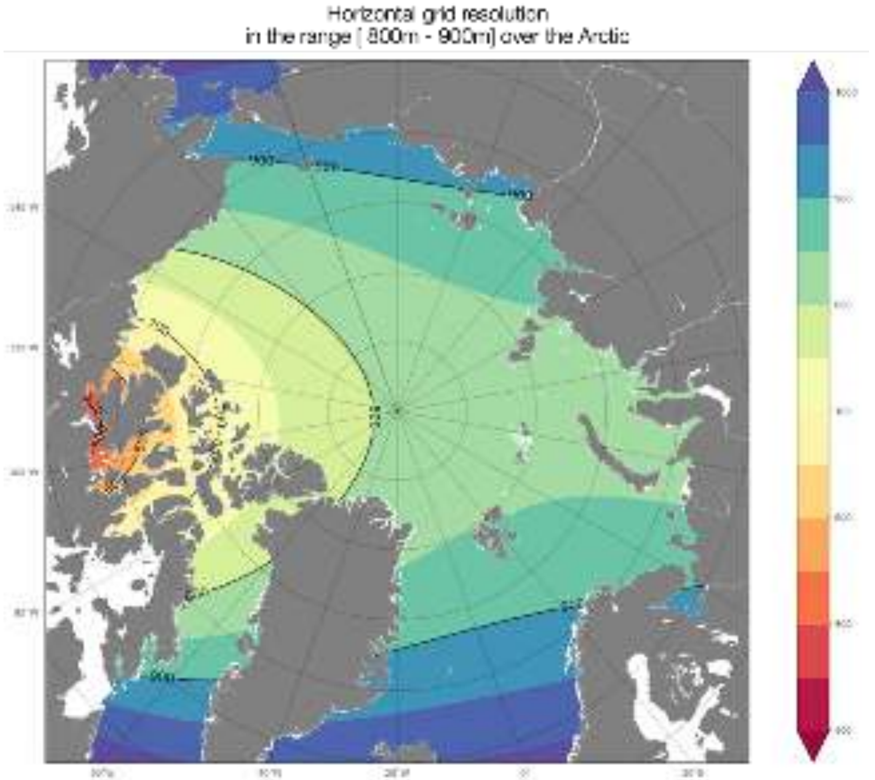
SI3
5 ice categories
EVP rheology

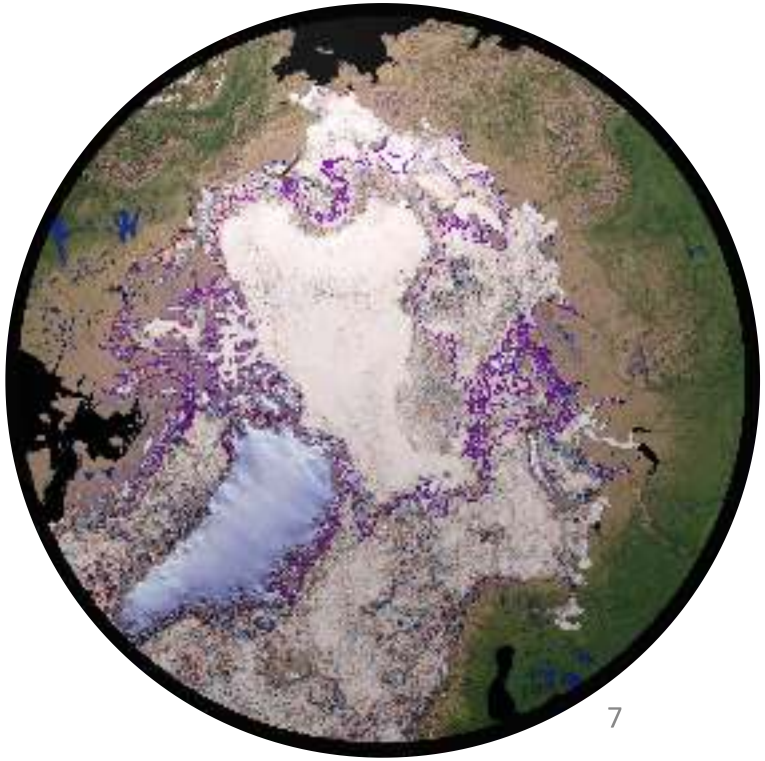
Prescribed Atmosphere

ERA 5
Bulk formula



Timmermans, M. & Marshall, J. *J Geophys Res Oceans* **125**, (2020).



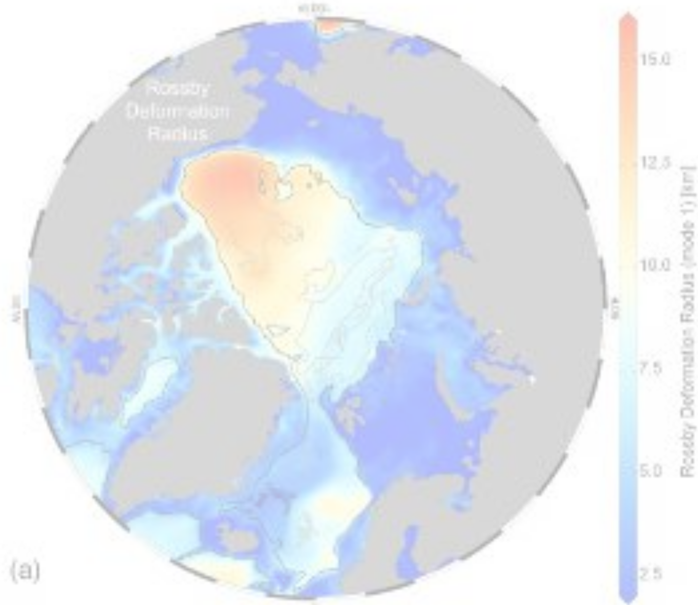


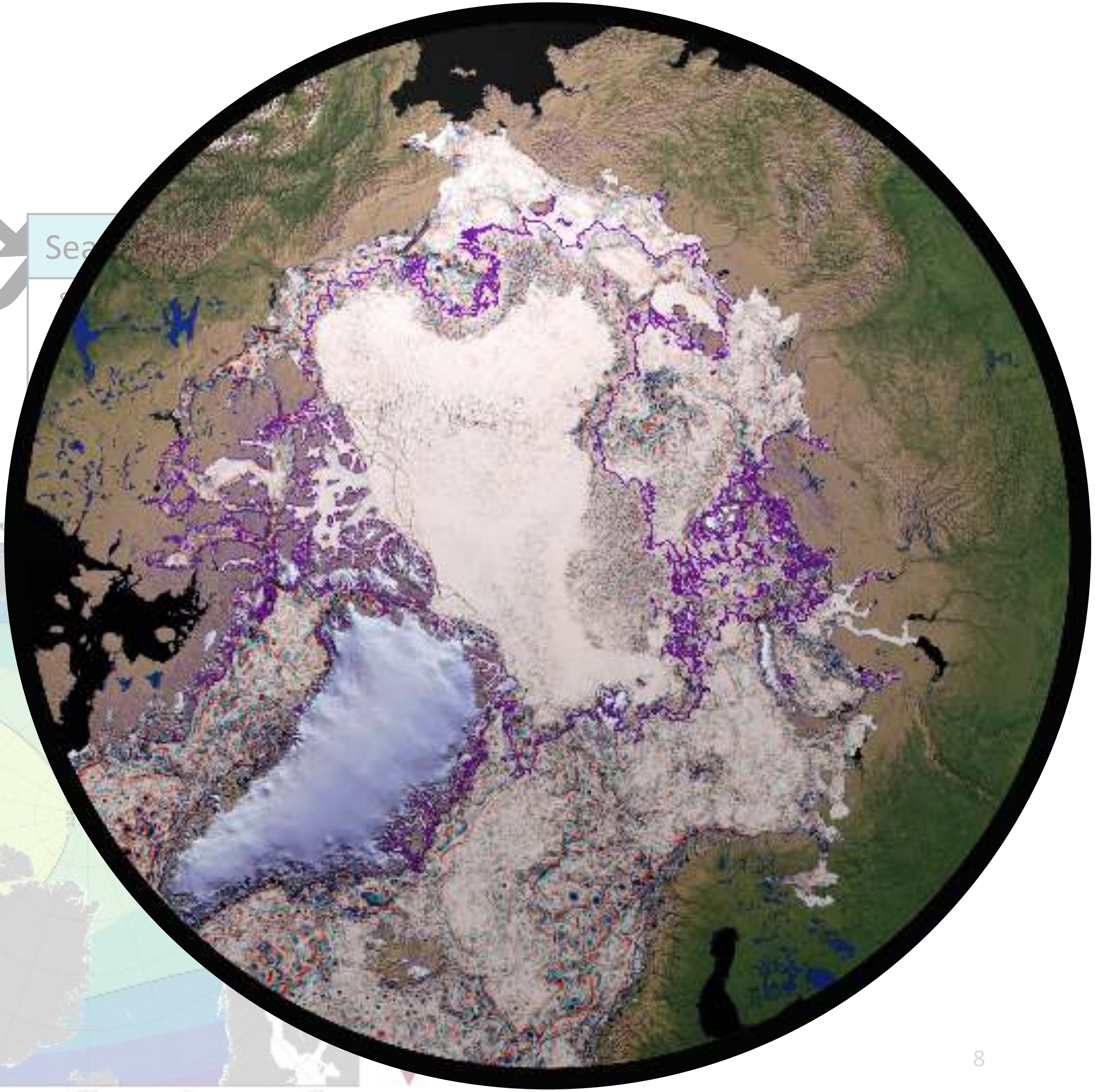
SEDNA

Ocean Model
NEMO 4.0.5 1/60° Resolution Pan-Arctic 150 vertical levels 7 year long experiment

Talandier & Lique 2023

Sea

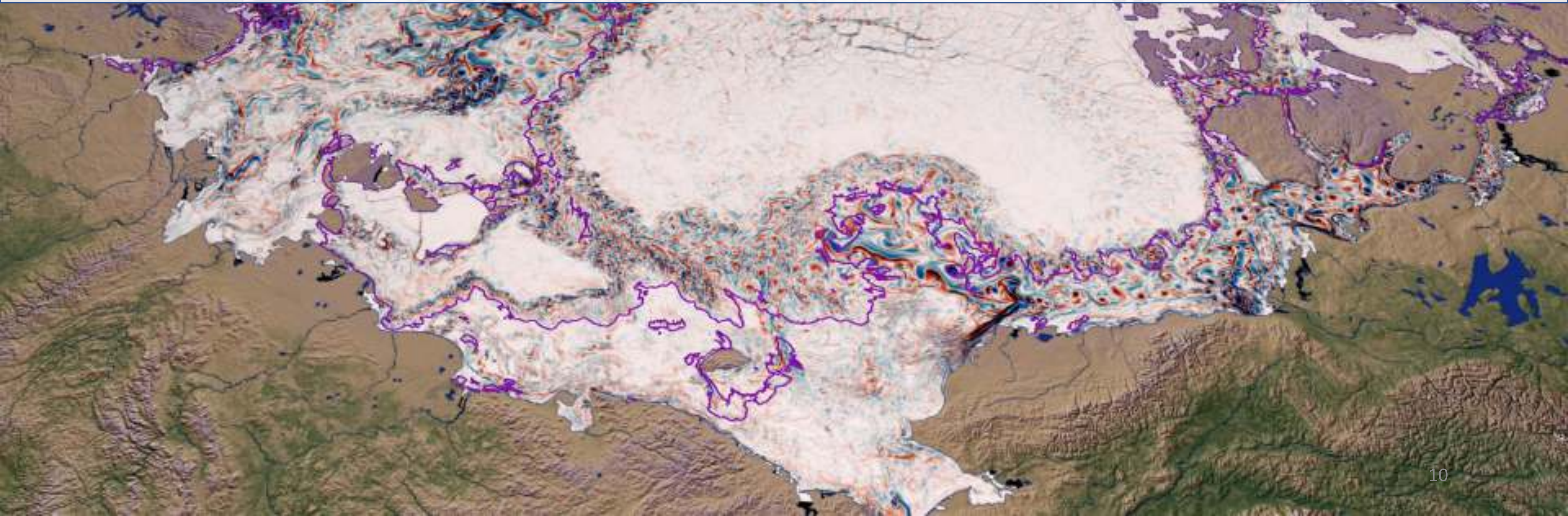




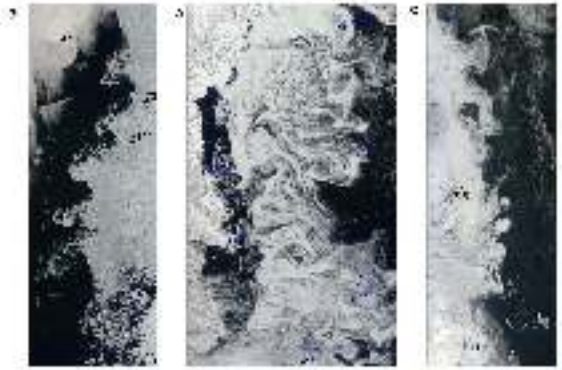
Timmermans, M. & Marshall, J. *J Geophys Res Oceans* **125**, (2020).

Eddies: Do they reshape the Sea-Ice Growth?

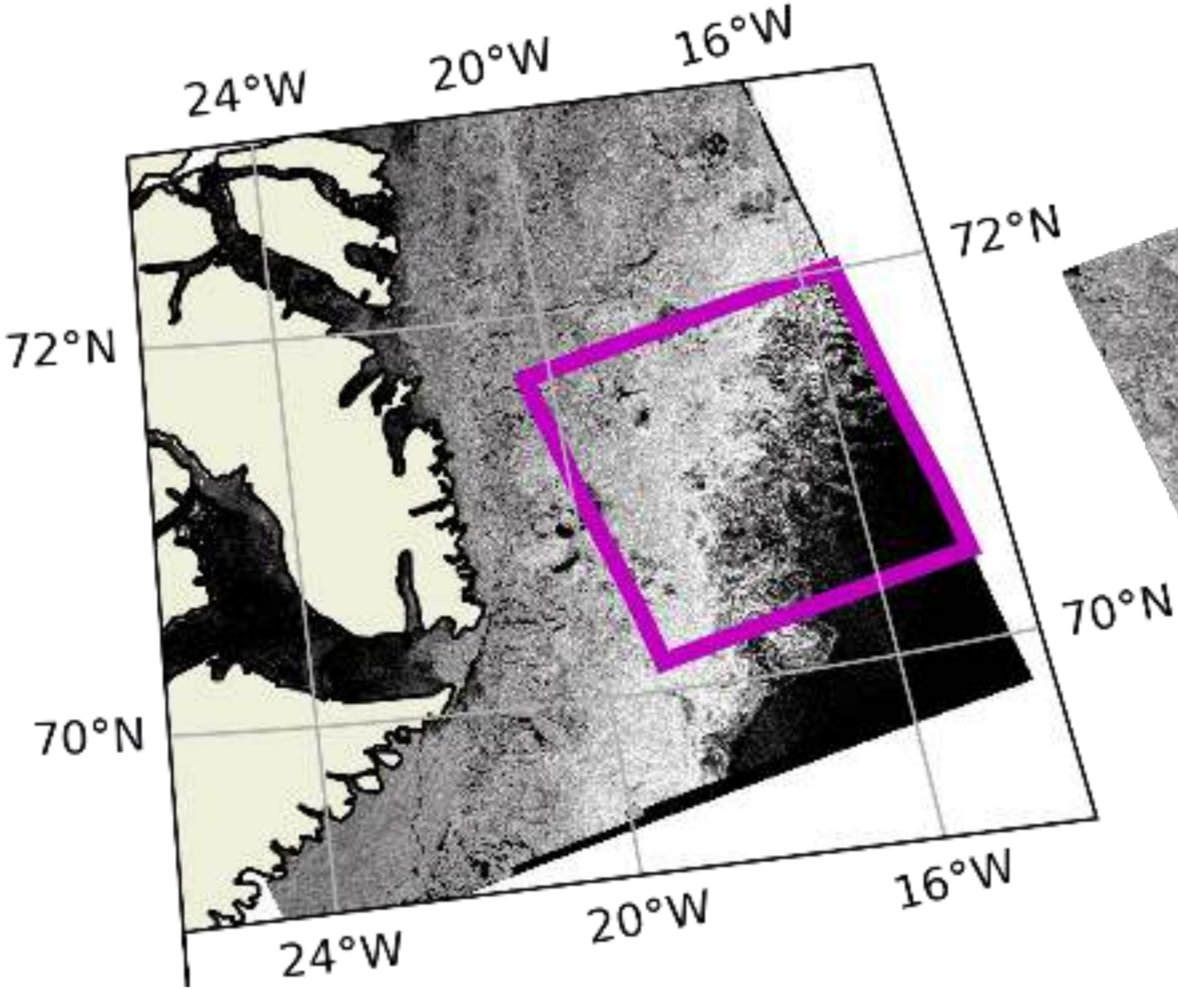
Martinez-Moreno et al. subm

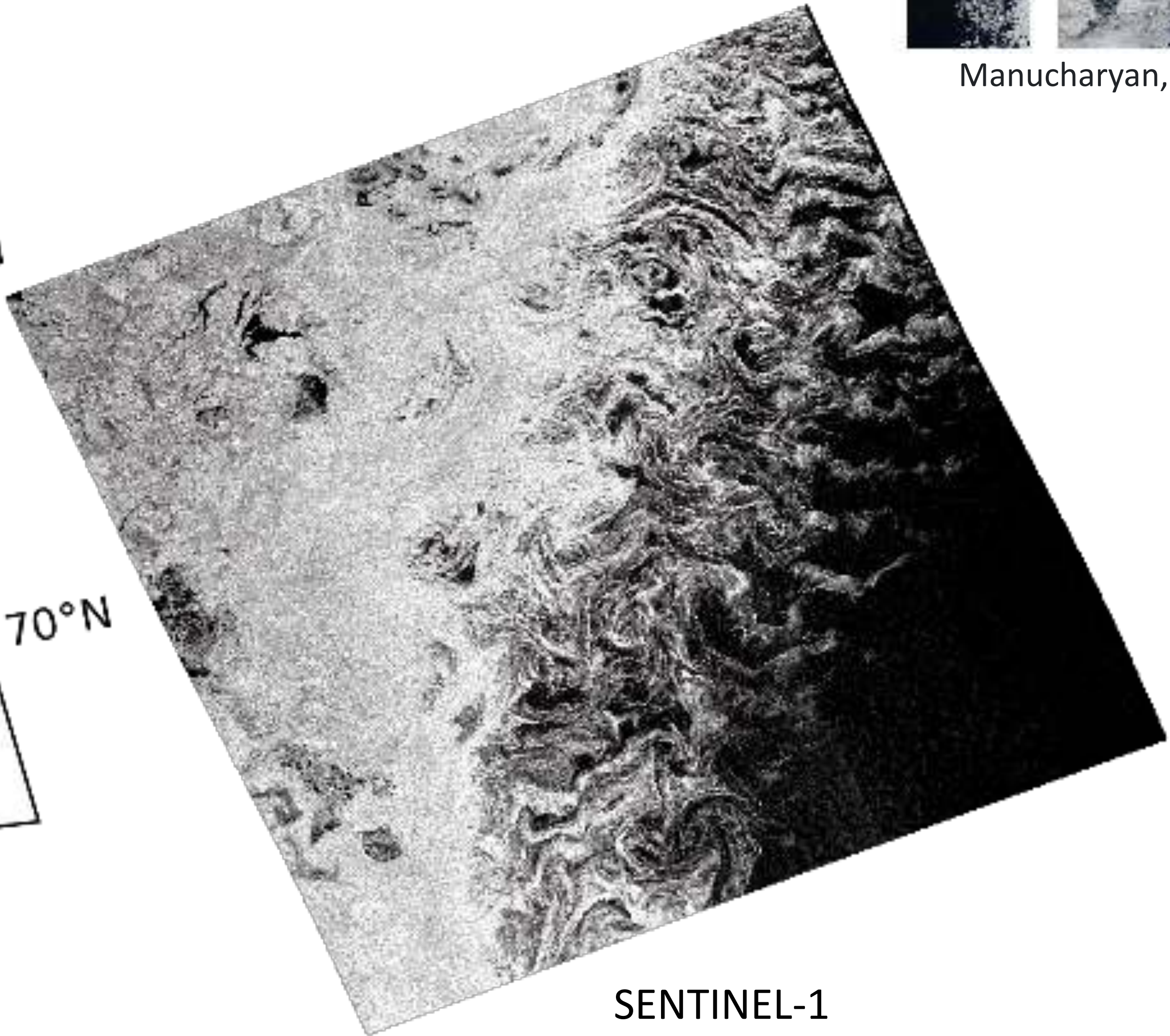


Sea-ice is spatially **heterogeneous**, where eddies of different scales have been observed since the 80's



Manucharyan, G. E. et al., 2017





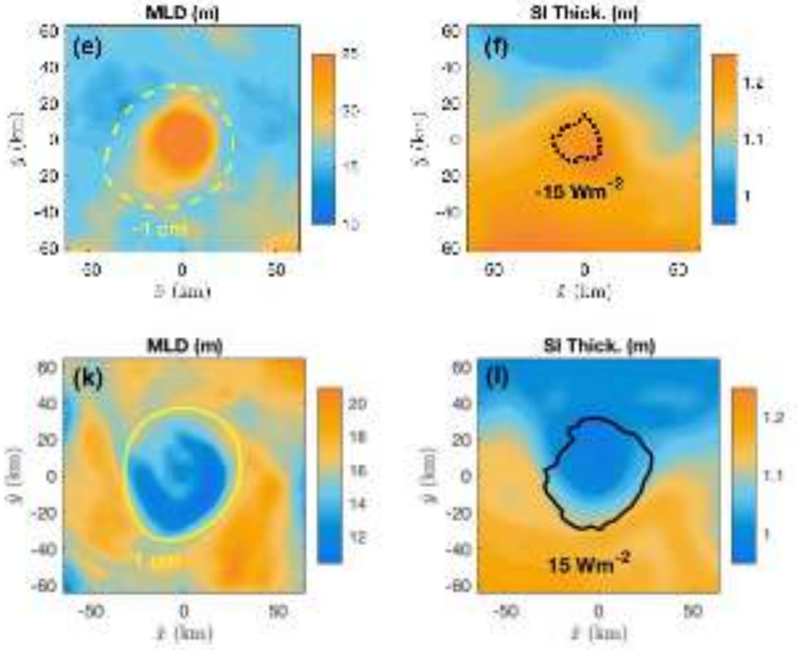
SENTINEL-1

Sea-ice eddy interactions

- Eddies have been shown to play a critical role in the melting and the drift of sea-ice:
  - Increase entrainment
  - Enhance in the Ekman vertical motion
  - Lateral advection

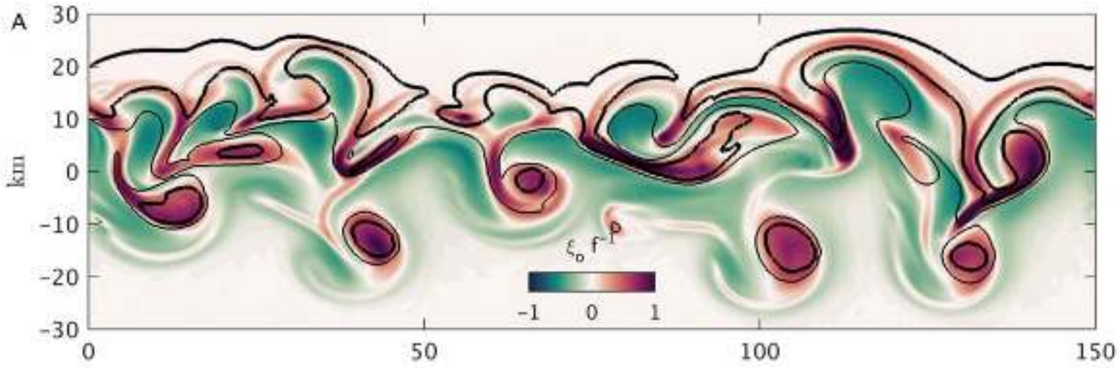
    (ice is accumulated in cyclonic filaments)

Eddy composites



Presence of eddies: decrease by 10% of the sea-ice thickness and a 60% shallowing of the MLD

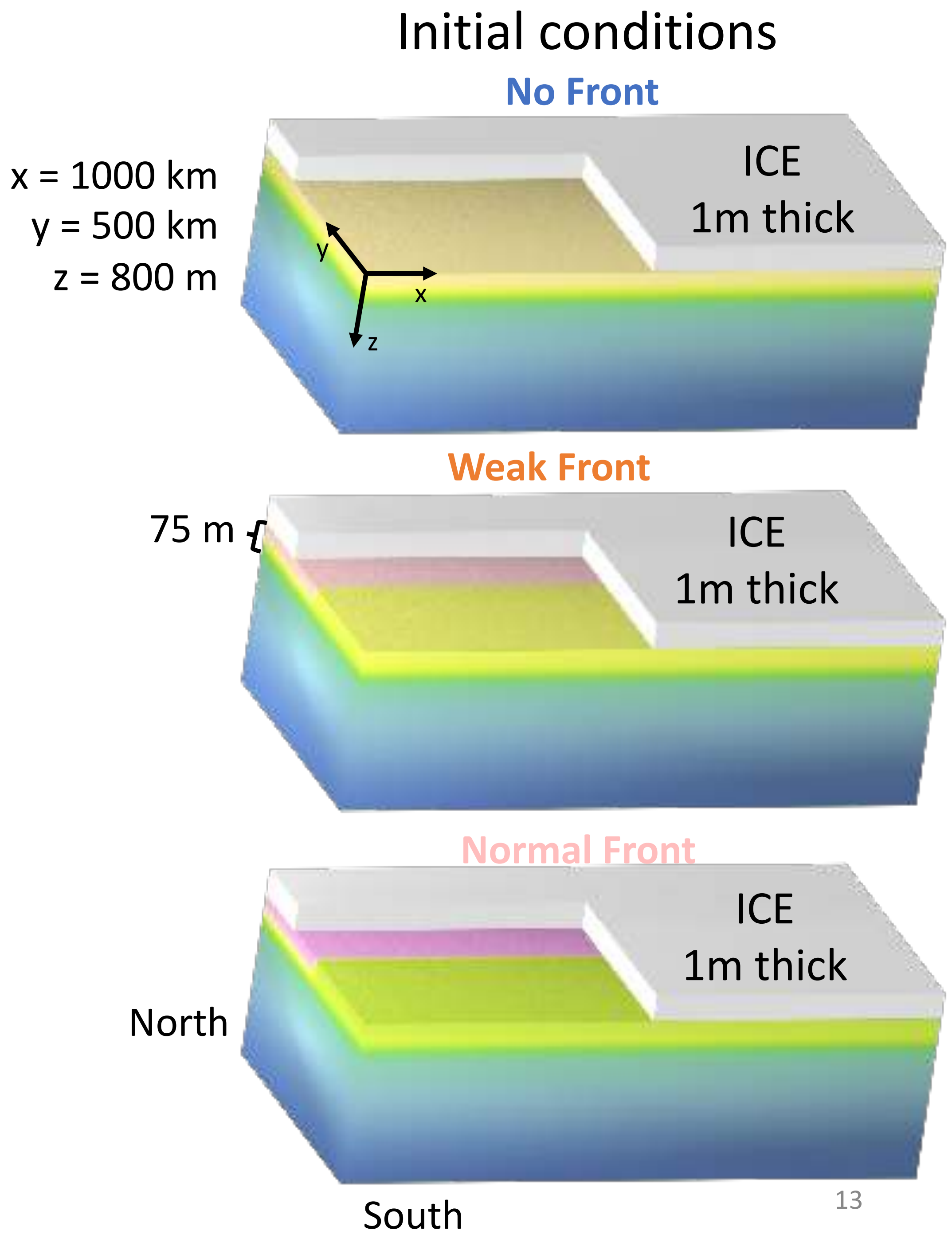
Gupta, M., et al., 2020



Manucharyan, G. E. & Thompson, A. F. Submesoscale Sea Ice-Ocean Interactions in Marginal Ice Zones. *J Geophys Res Oceans* **122**, 9455–9475 (2017).
Gupta, M., Marshall, J., Song, H., Campin, J. & Meneghello, G. Sea-Ice Melt Driven by Ice-Ocean Stresses on the Mesoscale. *J Geophys Res Oceans* **125**, (2020).

Let’s simplify our approach

- Three idealized configurations (NEMO + SI3) with different frontal intensities in the initial conditions:
  - No front ($\nabla S = 0 \ psu$)
  - Weak front ($\nabla S \approx 0.5 \ psu$)
  - Normal Front ($\nabla S \approx 1 \ psu$)
- Forced seasonally with radiation and air temperature
- No winds
- Small sea-ice velocities

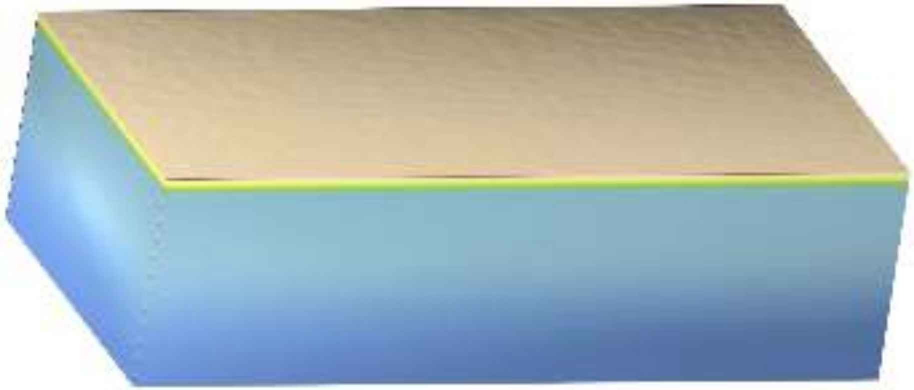


1 Year later …

- No front:
  - **Homogeneous** salinity and temperature.
  - Ice grows **homogeneously**
  - Domain is fully covered by ice in 1 day.
- Weak Front & Normal Front
  - Eddying salinity and temperature.
  - Variable freezing point.
  - Ice grows **heterogeneously**

Manucharyan, G. E. et al., 2017

No Front



Weak Front

Normal Front

1 Year later …

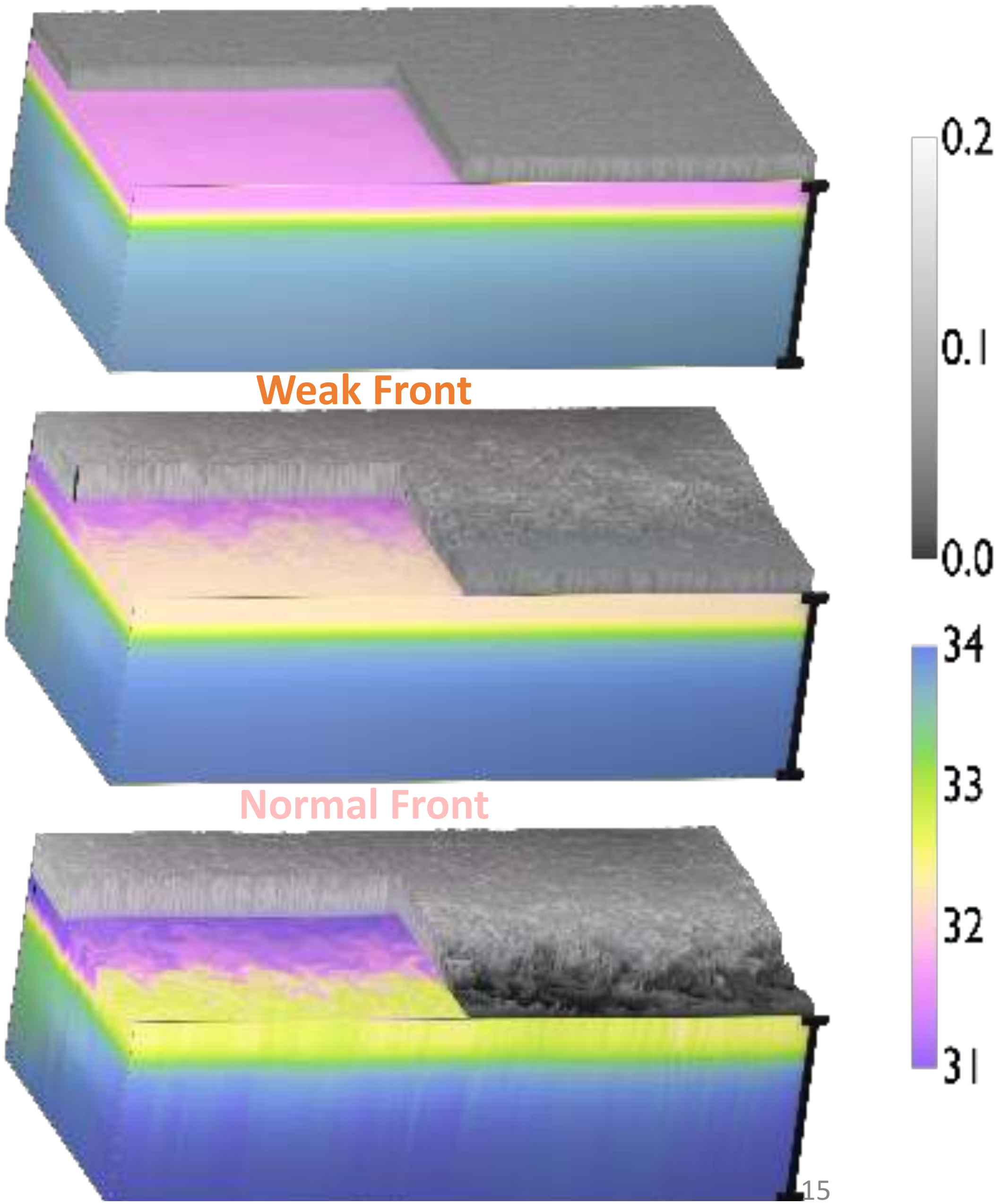
Snapshot
31st of December

- No front:
  - **Homogeneous** salinity and temperature.
  - Ice grows **homogeneously**
  - Domain is fully covered by ice in 1 day.

- Weak Front & Normal Front
  - Eddying salinity and temperature.
  - Variable freezing point.
  - Ice grows **heterogeneously**

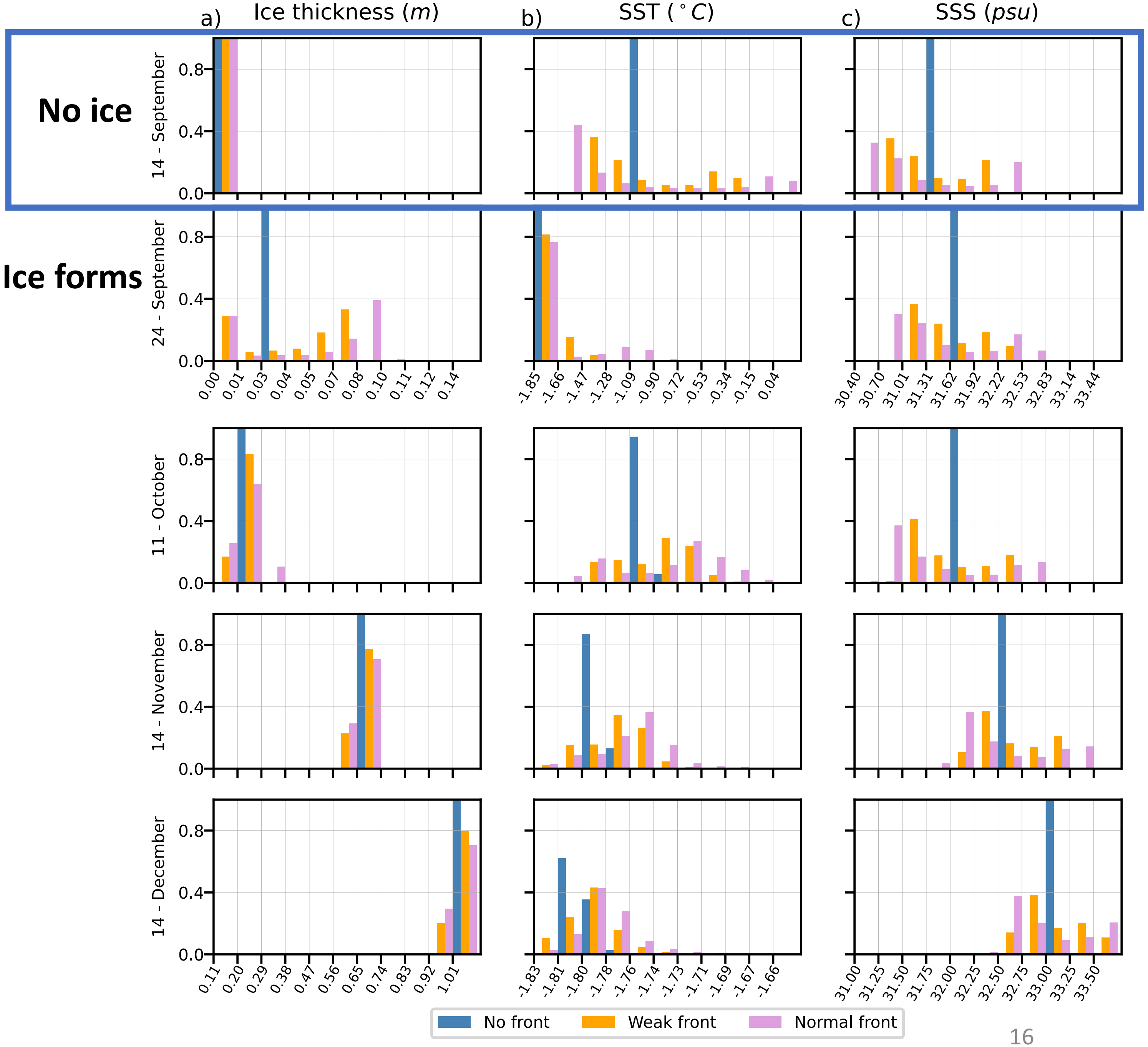
Eddy structures remain in the sea-ice.

Manucharyan, G. E. et al., 2017



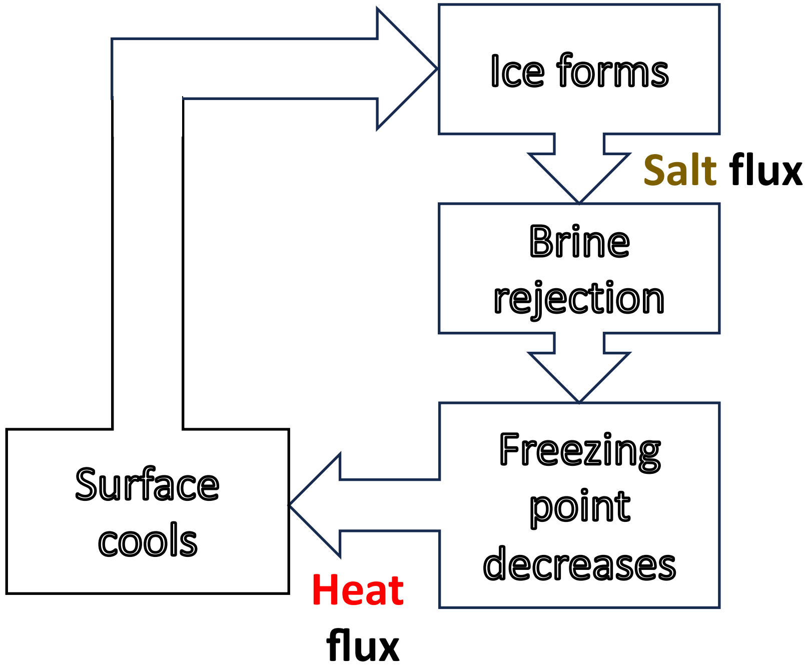
Eddies and sea-ice heterogeneity

- The no front responds homogeneously.
- The spatial variability in the weak and normal front is heterogeneous.
- The spatial variability is larger in the Normal front than in the Weak front



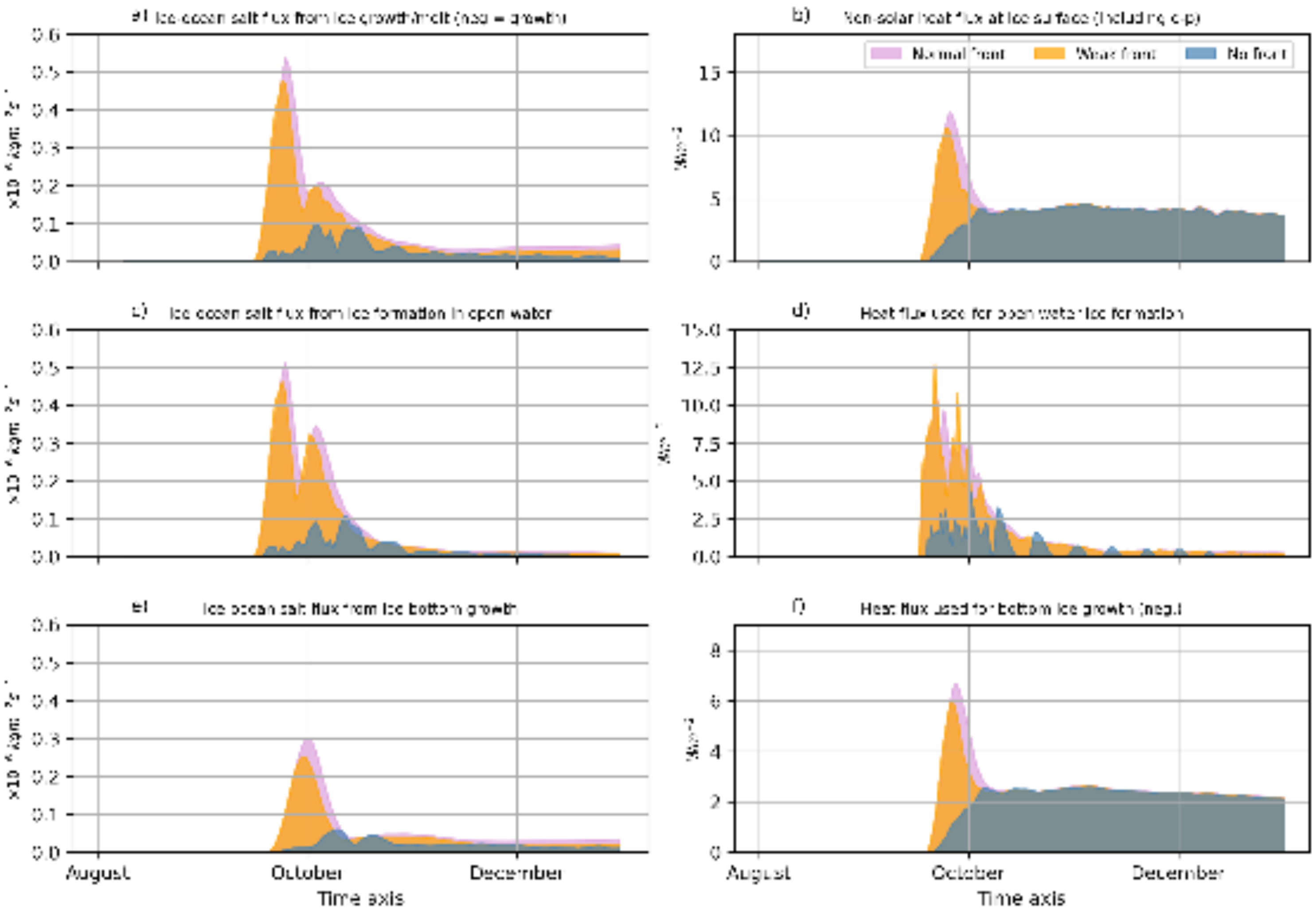
Sea-Ice fluxes

Heterogeneity in SST and SSS is transmitted to the ice through the **heat** and **salt** fluxes



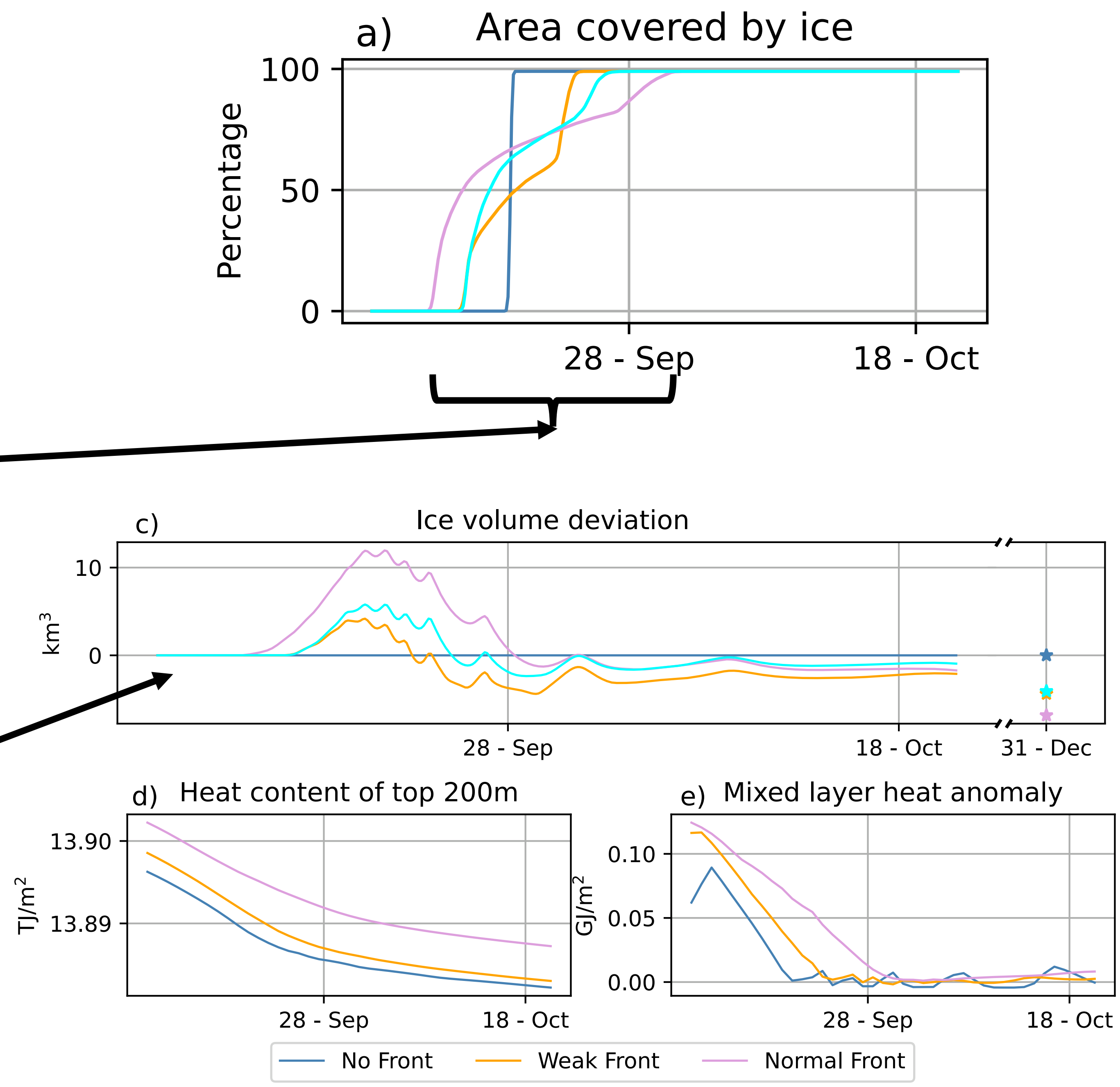
Salt flux Standard Deviation

Heat flux Standard Deviation



How eddies modify the sea-ice?

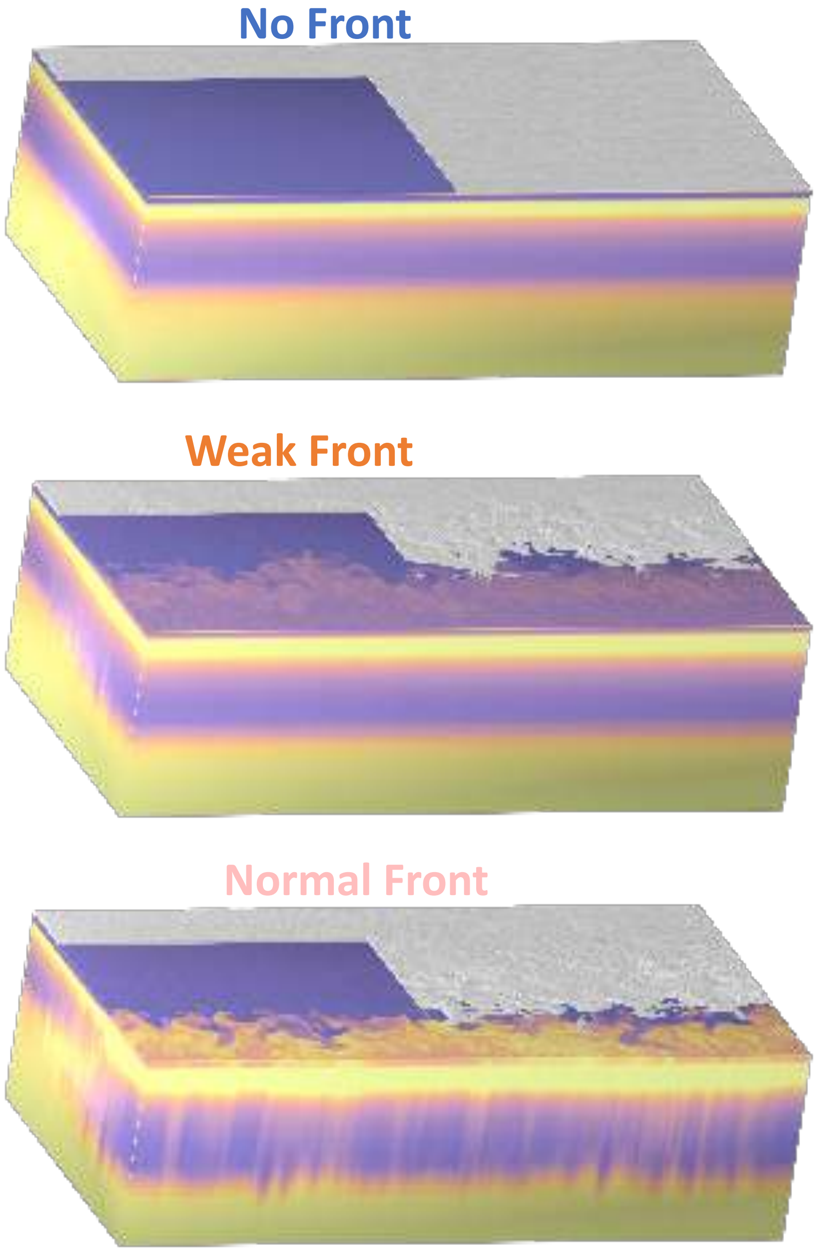
- Mesoscale eddies alter the start of ice formation.
- Mesoscale eddies lengthen the time-period to cover the domain
  - No front: 1 day
  - Weak front: 10 days
  - Normal front: 20 days
- Mesoscale eddies modify the total ice volume at the end of the season.
  - ∼1% less ice in the normal front compared to the no front



Why?

Take home messages

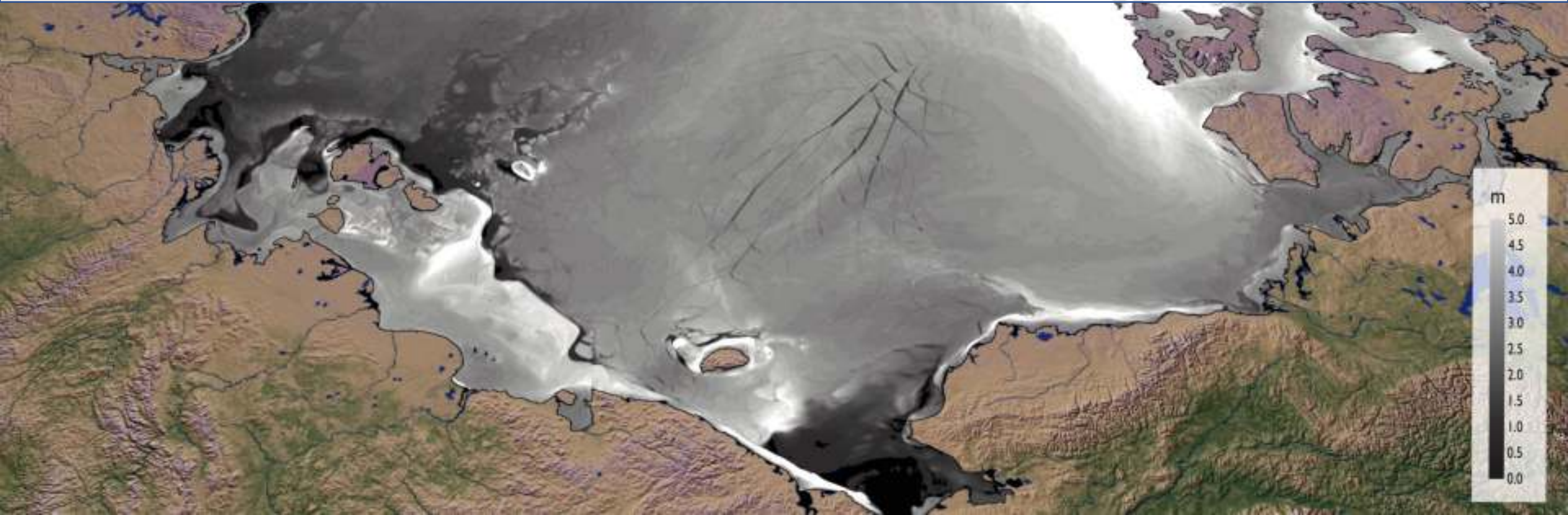
- The presence of eddies result in a more **heterogeneous** sea-ice
- Larger **heterogeneity** of sea-ice will likely result in a more brittle sea-ice
- A stronger eddy field would likely impact the ice production and extend the winter season



The ocean (ice) surface heterogeneity is necessary in order to adequately simulate the (ocean physics below) sea ice.

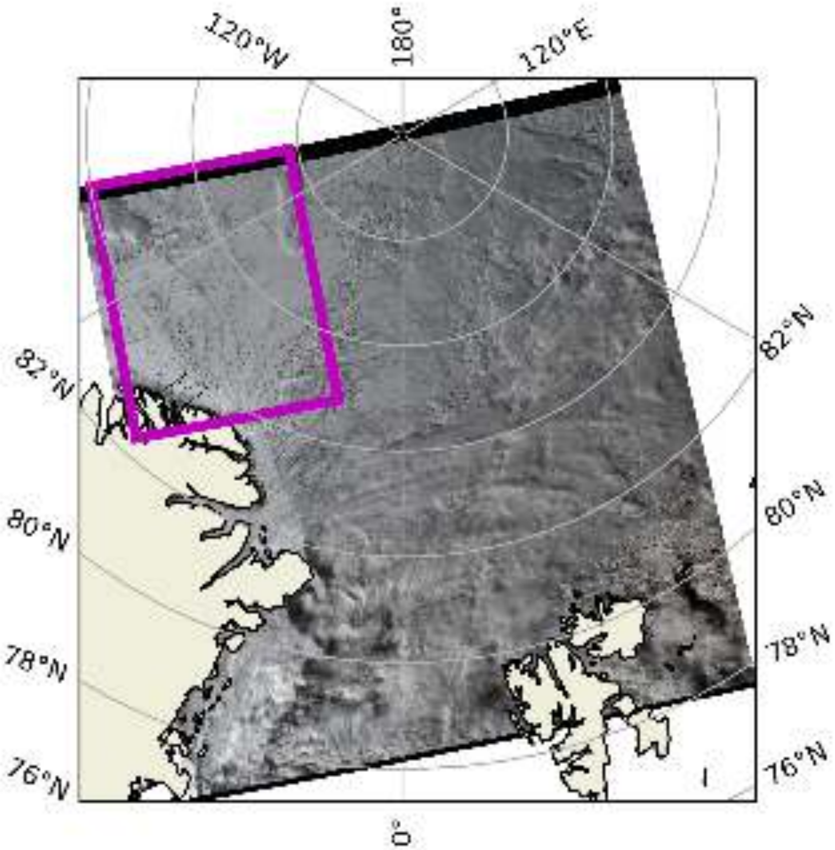
Linear Kinematic Features: Do they shape the sea-ice ocean dynamics in the Arctic?*

*Preliminary results

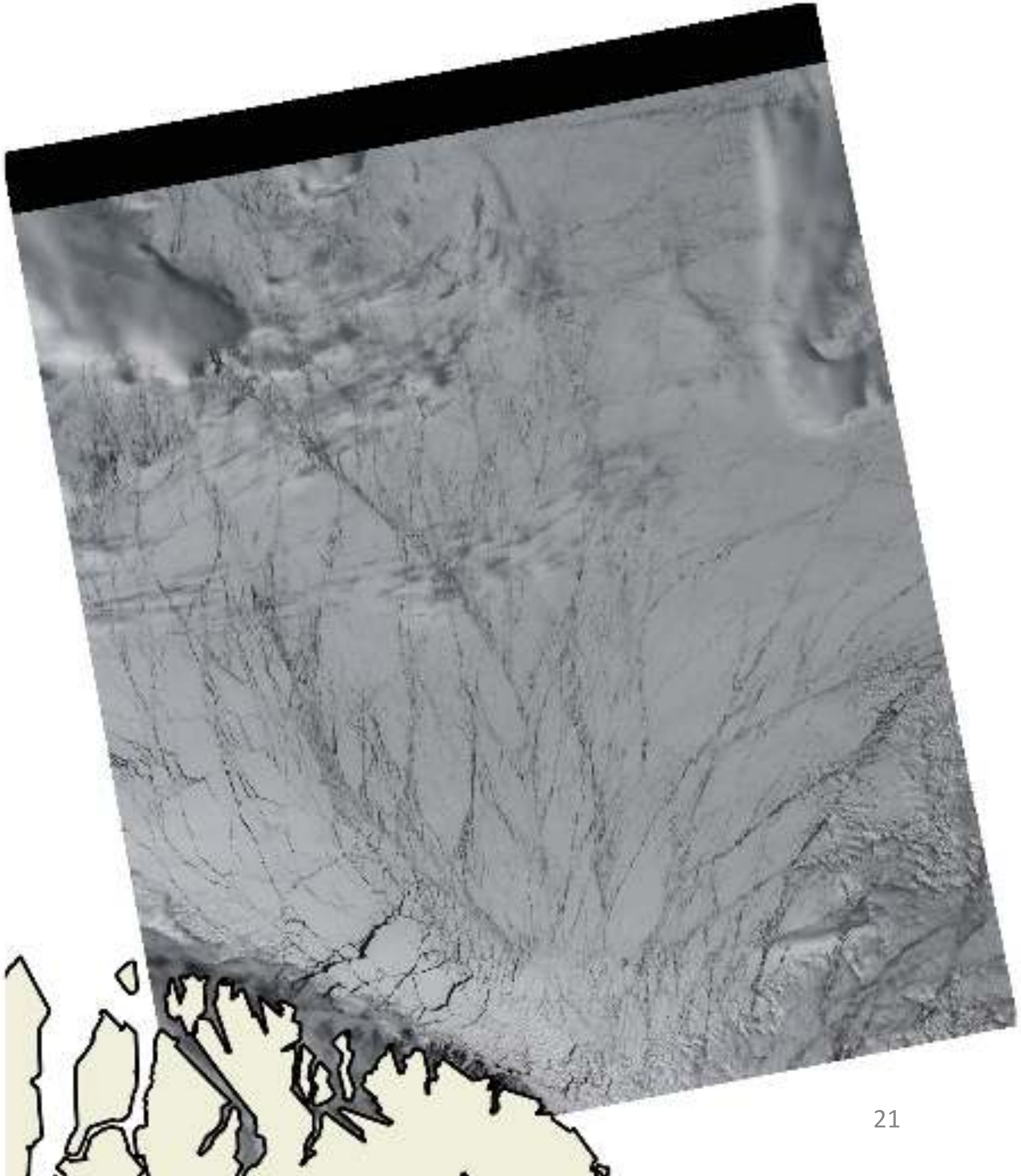


Linear Kinematic Features (LKF)

- Narrow linear sea ice deformations
- Localized and intensified ***deformation*** of the sea ice



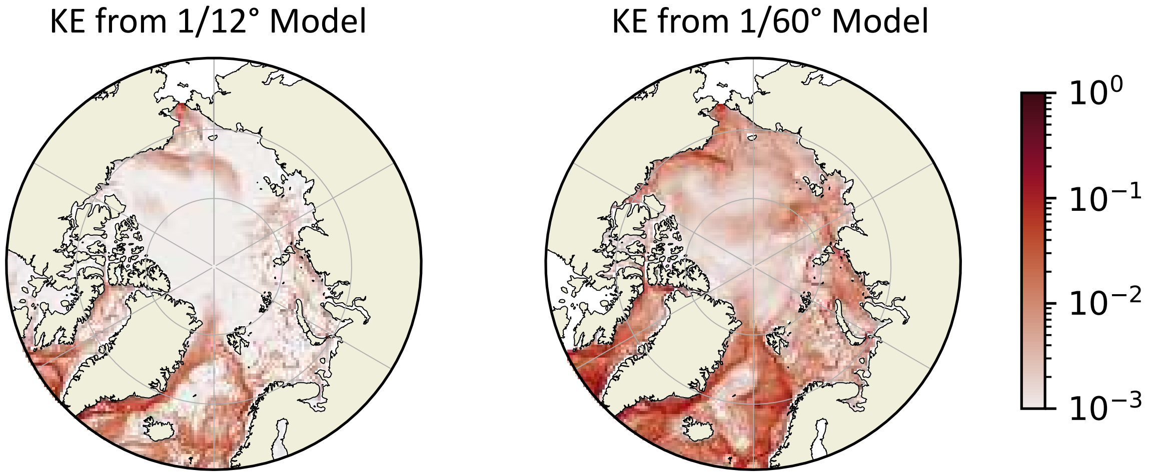
Sentinel 3 – True colour (11-June-2023)

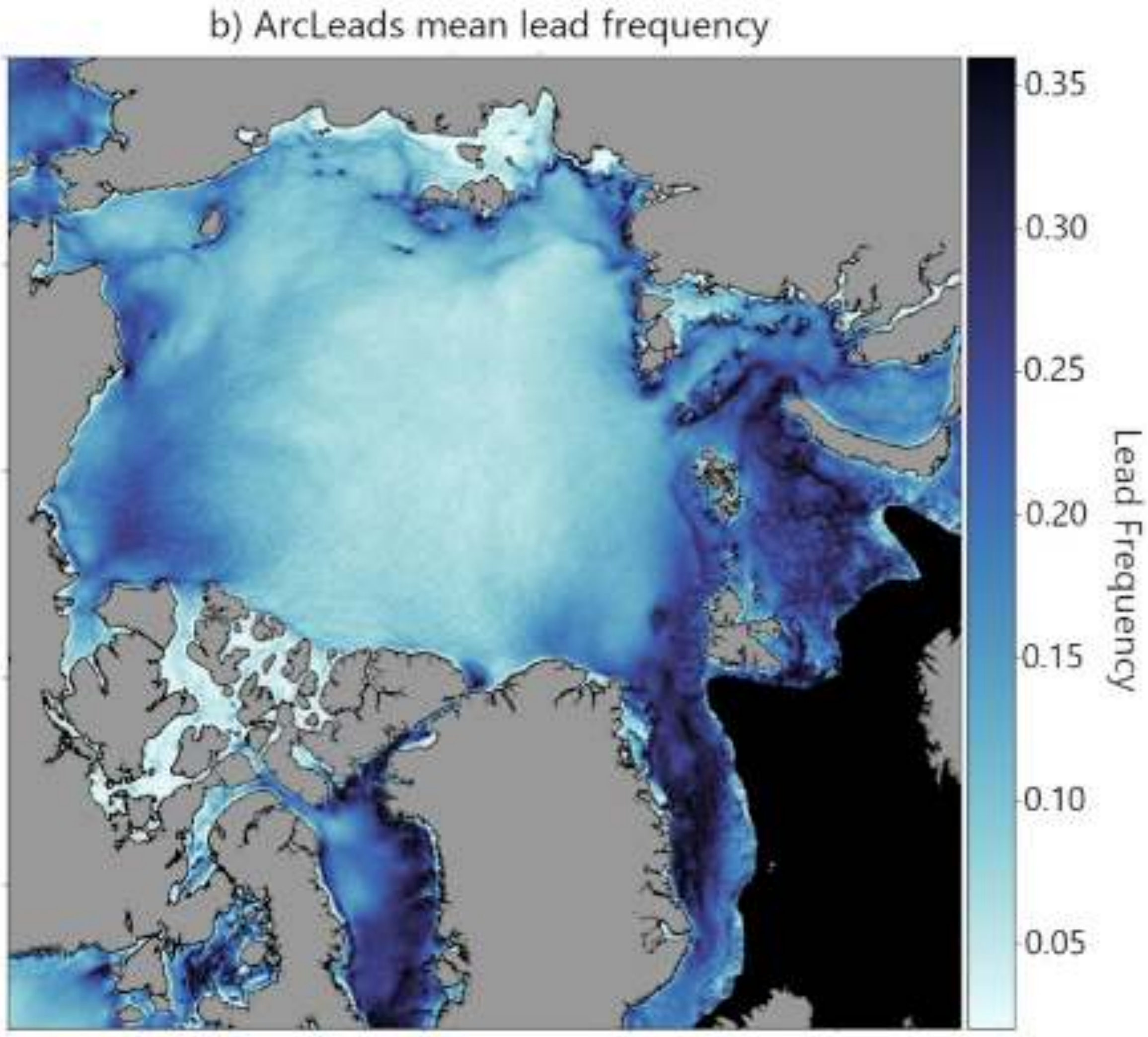



m
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0

Linear Kinematic Features (LKF)

- LKFs are spatial and temporal variable.
- The ocean + bathymetric features + winds originate the formation of LKF.
- The ocean can prime the sea-ice by making it more vulnerable to break-up.



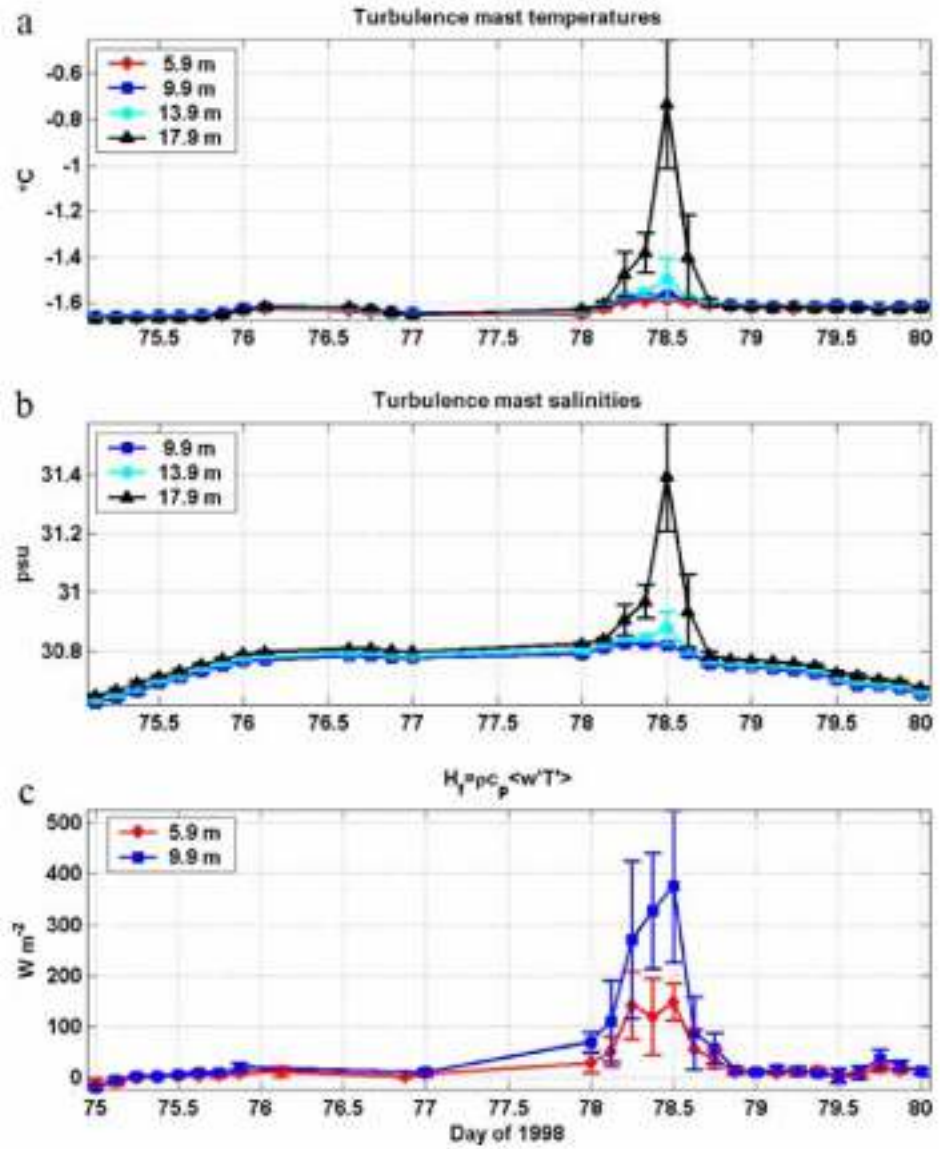


Climatology from 20-years of satellite observations

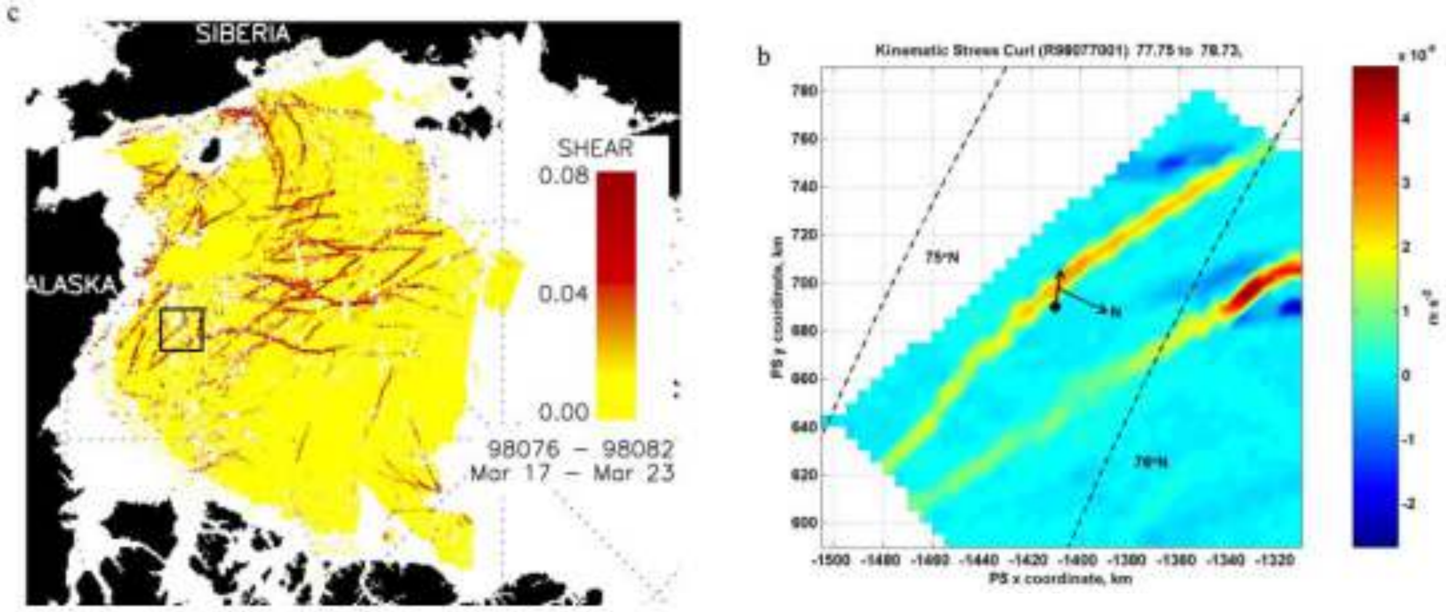
Willmes, S., Heinemann, G. & Schnaase, F. Patterns of wintertime Arctic sea ice leads and their relation to winds and ocean currents. *The Cryosphere Discuss.* **2023**, 1–23 (2023).

LKF influence in the ocean

- Large upwelling observed within the lead
- Observations suggest important heat exchanges between the ocean and atmosphere
- Suggest a concentrated Ekman transport in very small horizontal scales



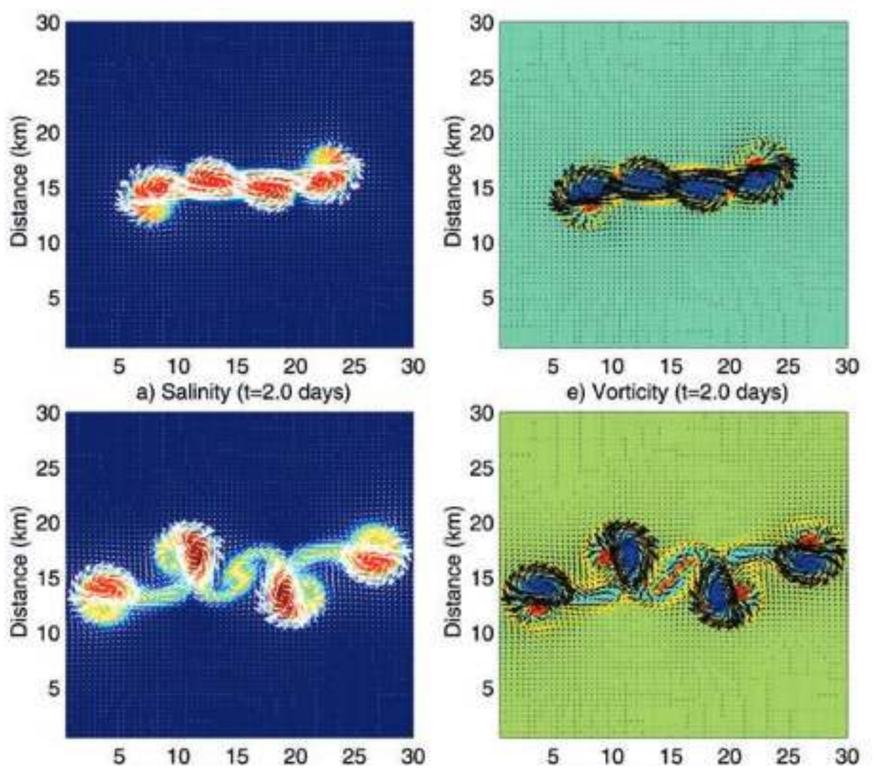
McPhee, M. G., Kwok, R., Robins, R. & Coon, M. Upwelling of Arctic pycnocline associated with shear motion of sea ice. *Geophys Res Lett* **32**, (2005).



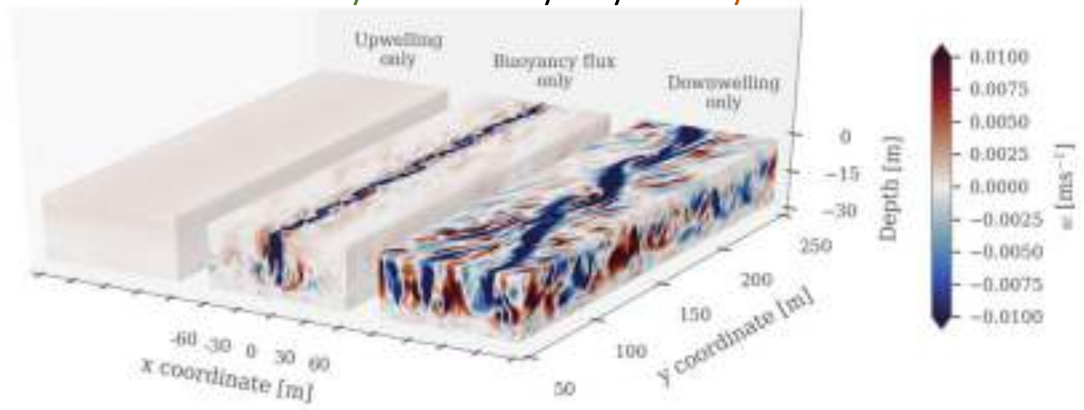
LKF influence in the ocean

- LKF generate MLD instabilities due to brine rejection
  - Salt rich eddies
  - Eddy scale proportional to buoyancy forcing

- Large-eddy simulations show:
  - Cyclonic shear = No turbulence
  - Anticyclonic shear = Strong turbulence (100Wm^{-2})
  - Buoyancy flux from freezing increase turbulent flux.



Cyclonic Buoyancy Anticyclonic



"Leads represent only a small fraction of the sea-ice cover, but their presence changes the interaction of sea ice with the ocean and atmosphere in the Arctic climate system **substantially**."

Hutter, N. *et al.*, (2022).

How much is substantially?

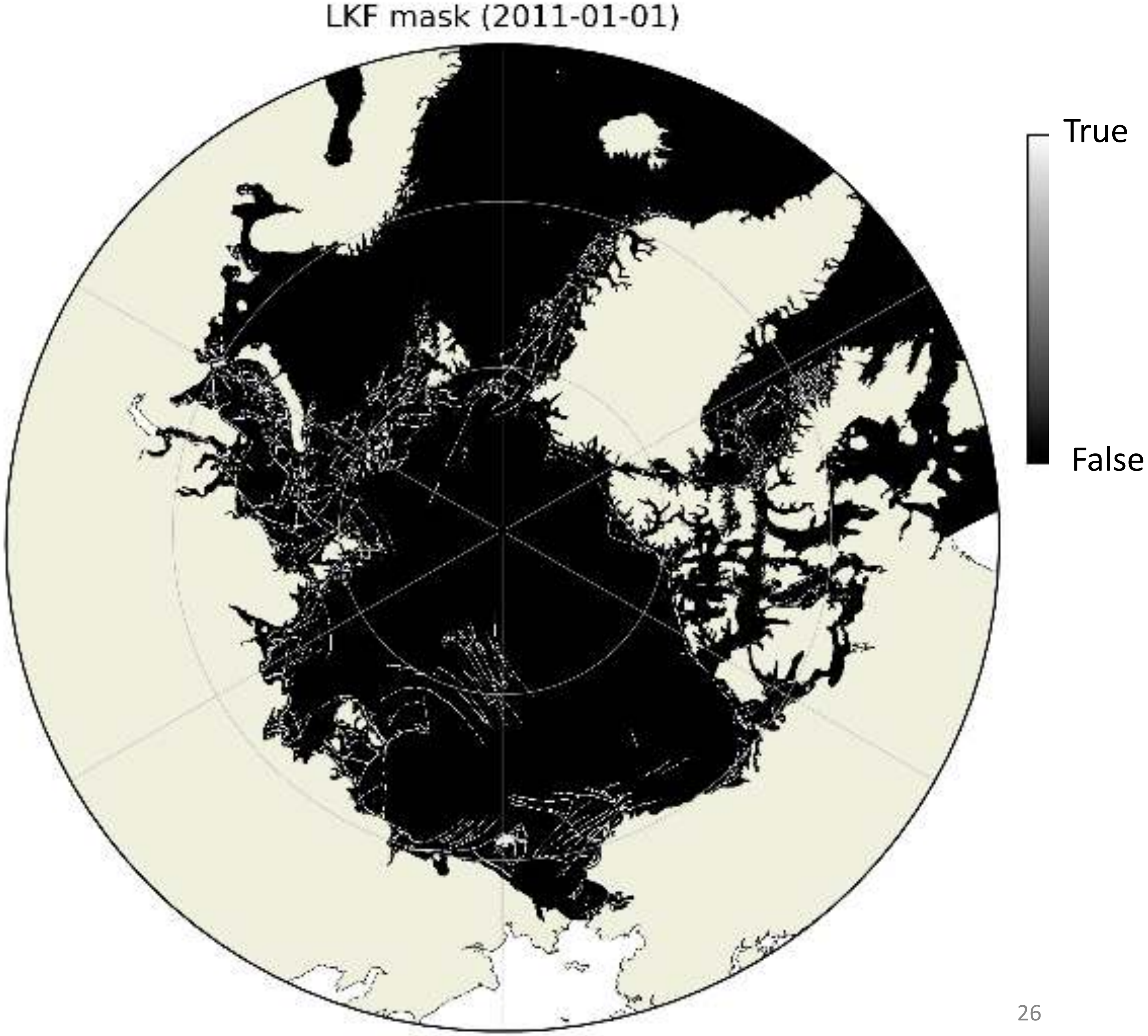
Smith, D. C., Lavelle, J. W. & Fernando, H. J. S. *J. Geophys. Res. Oceans* **107**, 17-1-17–17 (2002).
Bourgault, P., Straub, D., Duquette, K., Nadeau, L.-P. & Tremblay, B. *J. Phys. Oceanogr.* **50**, 2189–2202 (2020).

LKF detection method

Modified algorithm proposed by Hutter, N., et. al. (2019)

$$T_d = \sqrt{\underbrace{\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)}_{Divergence}^2 + \underbrace{\left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2}_{Shear\ Magnitude}}$$

Recover a mask of the LKF

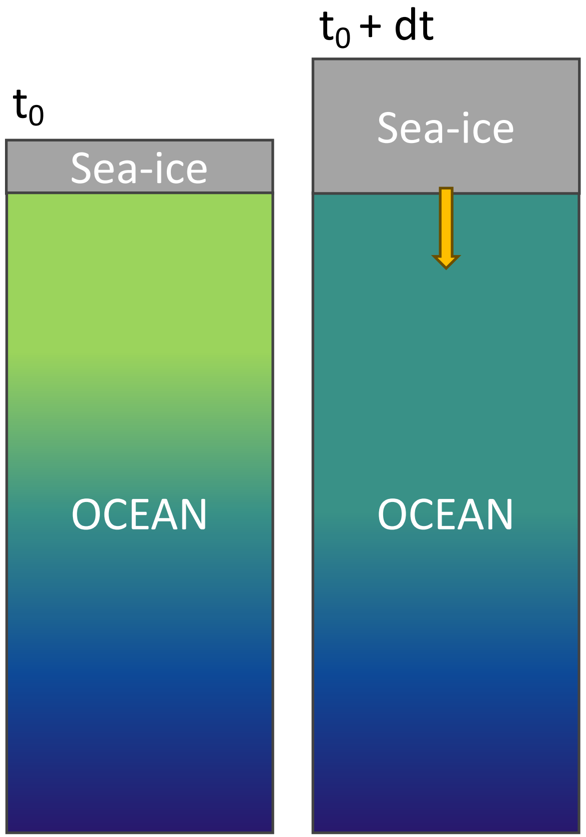


Hutter, N., Zampieri, L. & Losch, M. Leads and ridges in Arctic sea ice from RGPS data and a new tracking algorithm. *The Cryosphere* **13**, 627–645 (2019).

Surface freshwater fluxes

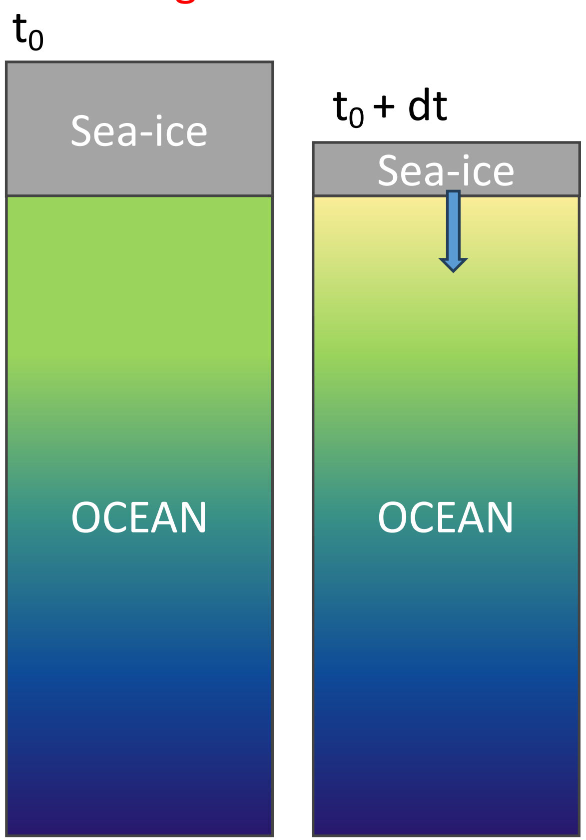
(sea-ice/ocean interaction)

Freezing

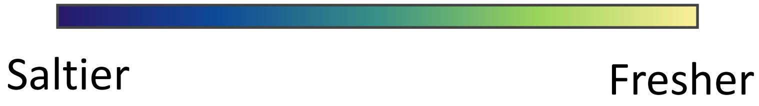


- Ice growths
- Brine rejection
- Salinity increases
- Freshwater transport to sea-ice

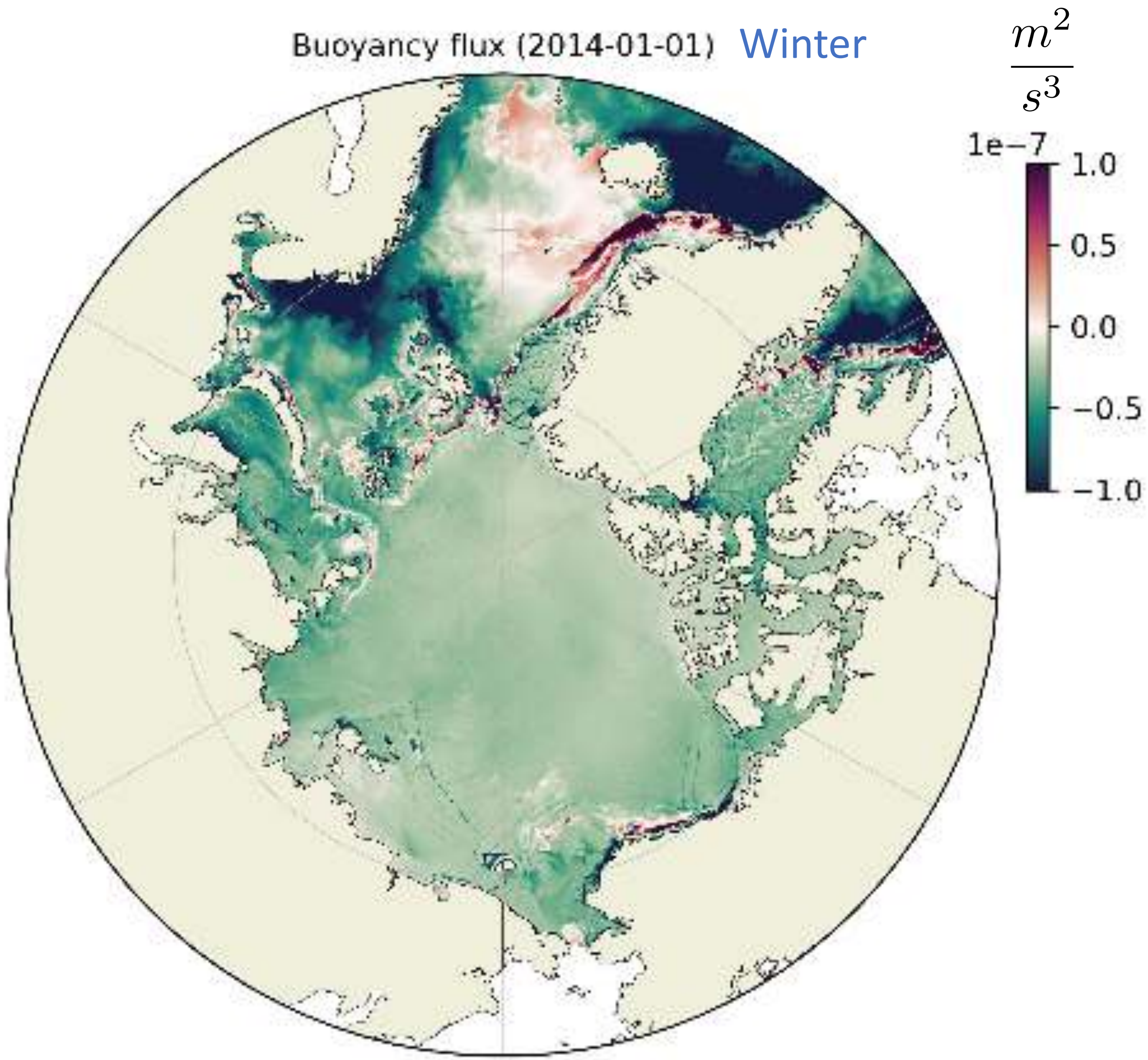
Melting

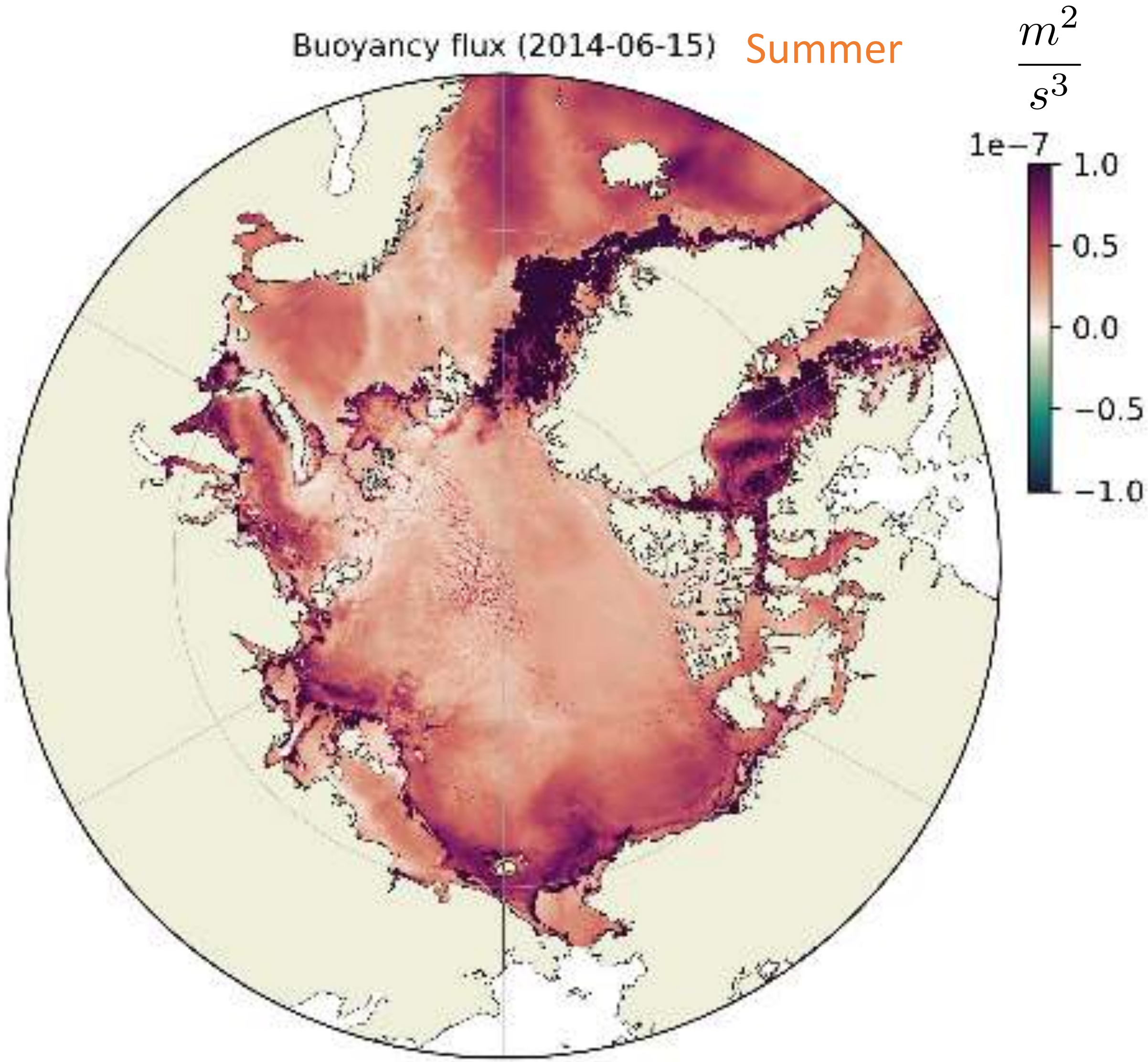


- Ice shrinks
- Melt freshwater
- Salinity decreases
- Freshwater transport to ocean



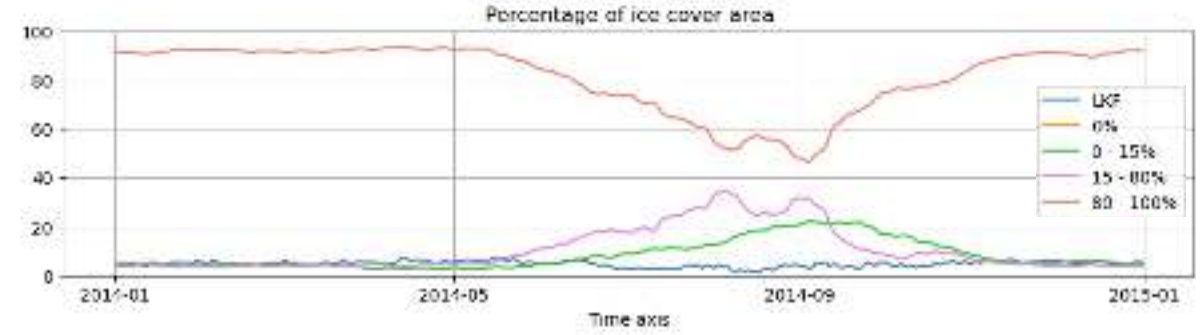
Buoyancy Flux





Positive = Less dense

Buoyancy fluxes

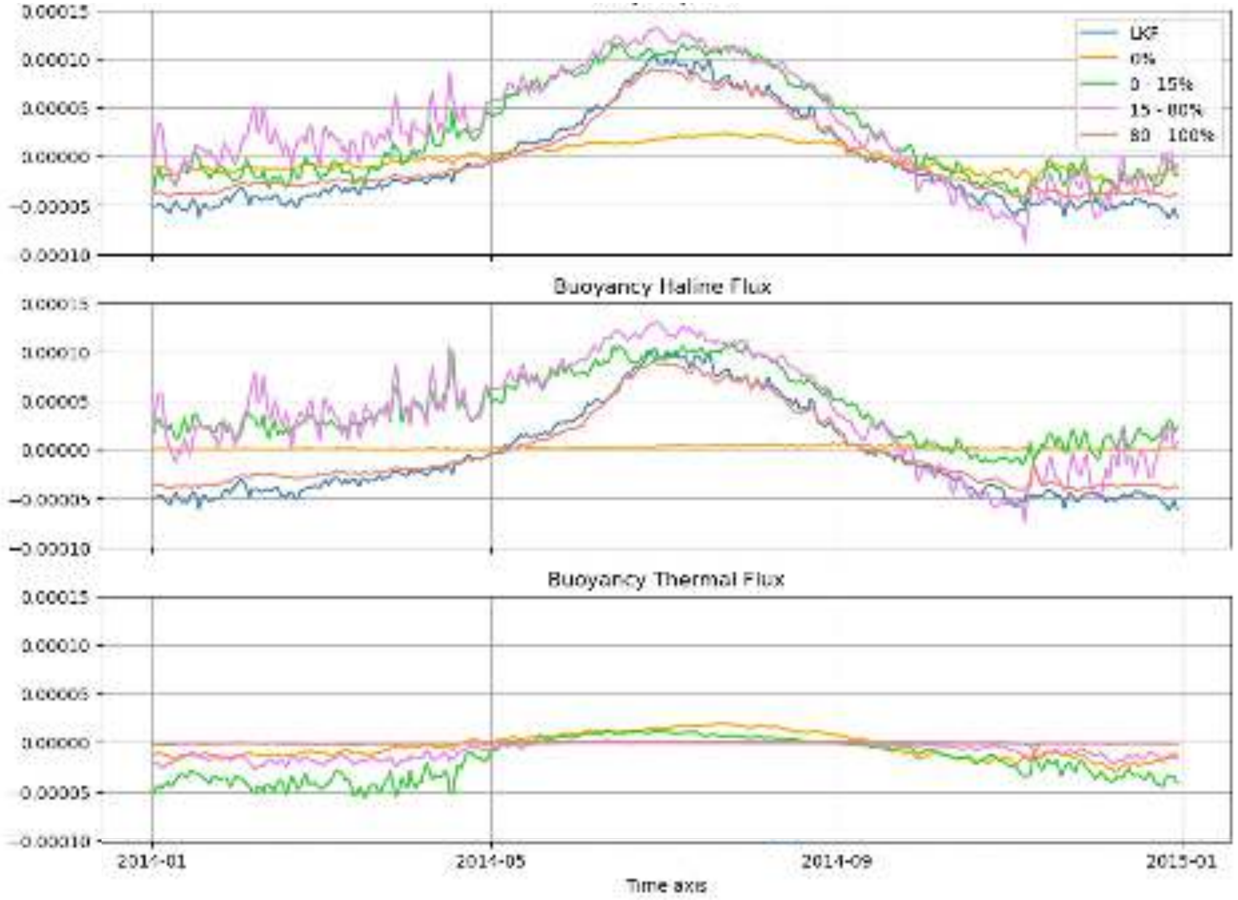


- LKF represents less than 5% of the surface of the ice pack
- Buoyancy forcing through LKF are comparable to the total flux through the pack

  (Significant contribution to the total buoyancy flux)
- Haline contribution is larger than heat contribution:
  - Sea-ice formation within LKFs
  - Arctic being a β-ocean

$$B_F = \underbrace{\frac{g\alpha}{\rho}\frac{Q_{net}}{C_p}}_{Thermal\ component} \underbrace{-\beta g\left(E-P\right)SSS}_{Haline\ component}$$

Buoyancy flux kg/s



The buoyancy flux in the LKF is 20 – 30 %
Larger than in the ice pack

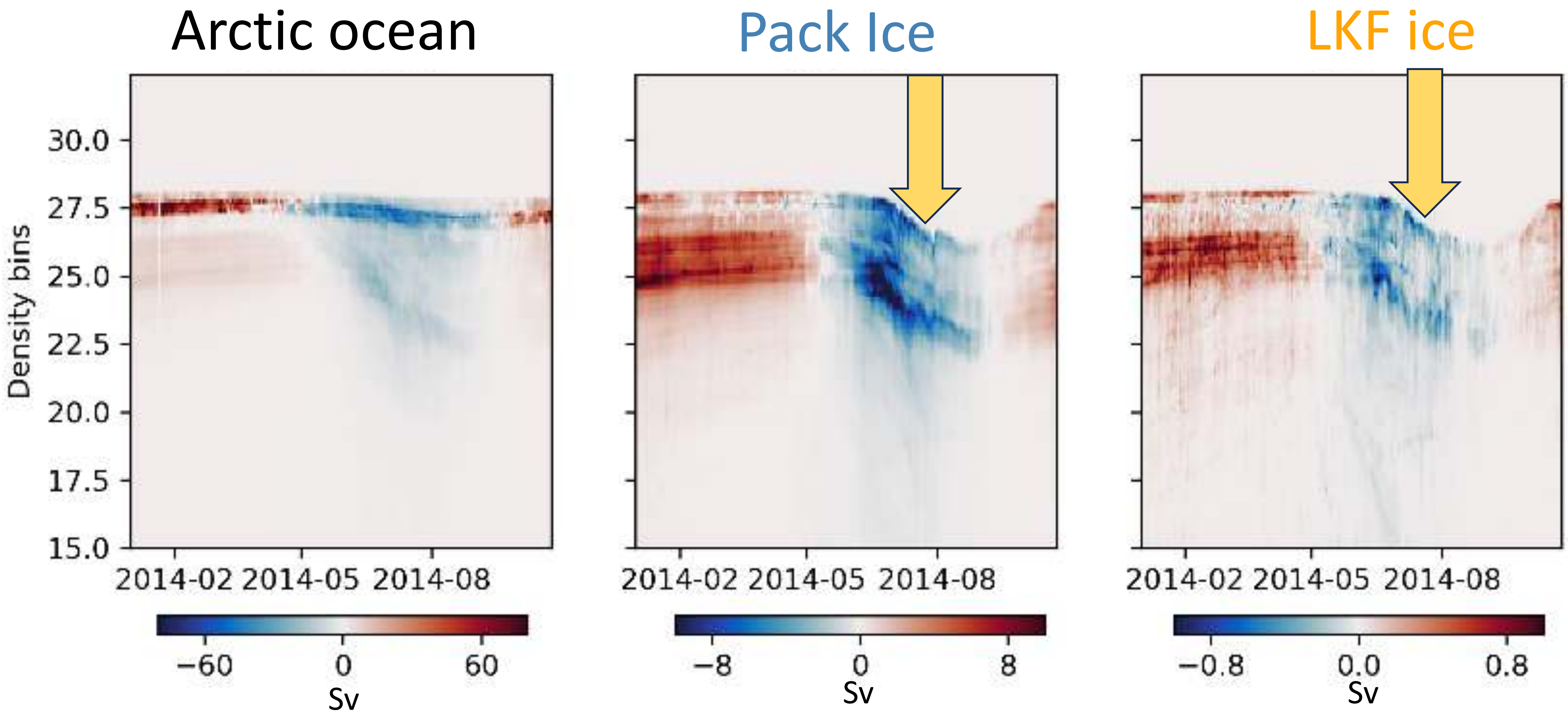
Water Mass Transformation (Walin 1982)

- "**Water mass transformation**" refers to the process in which the properties of a water parcel are changed by the surface forcing.
- Characterize the role of different processes (sea-ice) driving ocean circulation.
- The density of the water parcel may change due to the surface fluxes and ultimately affect the ocean dynamics.

$$\Omega(\sigma_k, t) = \underbrace{-\frac{1}{\sigma_{k+1} - \sigma_k} \iint_A \left(\frac{\alpha Q_{net}}{\rho_0 C_p} \right) dA}_{Net\ surface\ heat\ flux} + \underbrace{\frac{1}{\sigma_{k+1} - \sigma_k} \iint_A \left(\frac{\beta F_{net} SSS}{\rho_0} \right) dA}_{Net\ surface\ freshwater\ flux}$$

Positive transformation rate = Denser (Lose buoyancy)
Negative transformation rate = Lighter (Gain buoyancy)

Water Mass Transformation (Walin 1982)



Positive transformation rate = Denser (Lose buoyancy)
Negative transformation rate = Lighter (Gain buoyancy)

Water Mass Formation (Nurser et al. 1999)

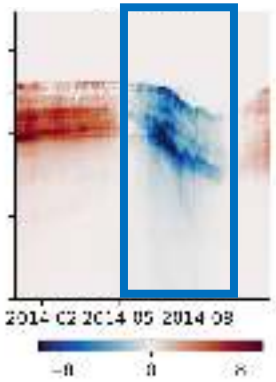
$$\Omega(\sigma_k, t) = \underbrace{-\frac{1}{\sigma_{k+1} - \sigma_k} \iint_A \left(\frac{\alpha Q_{net}}{\rho_0 C_p}\right) dA}_{Net\ surface\ heat\ flux} + \underbrace{\frac{1}{\sigma_{k+1} - \sigma_k} \iint_A \left(\frac{\beta F_{net} SSS}{\rho_0}\right) dA}_{Net\ surface\ freshwater\ flux}$$

$$\overline{M(\sigma_k)} = -\left[\overline{\Omega(\sigma_{k+1})} - \overline{\Omega(\sigma_k)}\right]$$

Formation describes the convergence (positive M) or divergence (negative M) of transformation between the isopycnals σ_k and σ_{k+1}.

Positive formation rate = Water convergence (Downwelling)
Negative formation rate = Water divergence (Upwelling)

Water Mass Formation (Nurser et al. 1999)



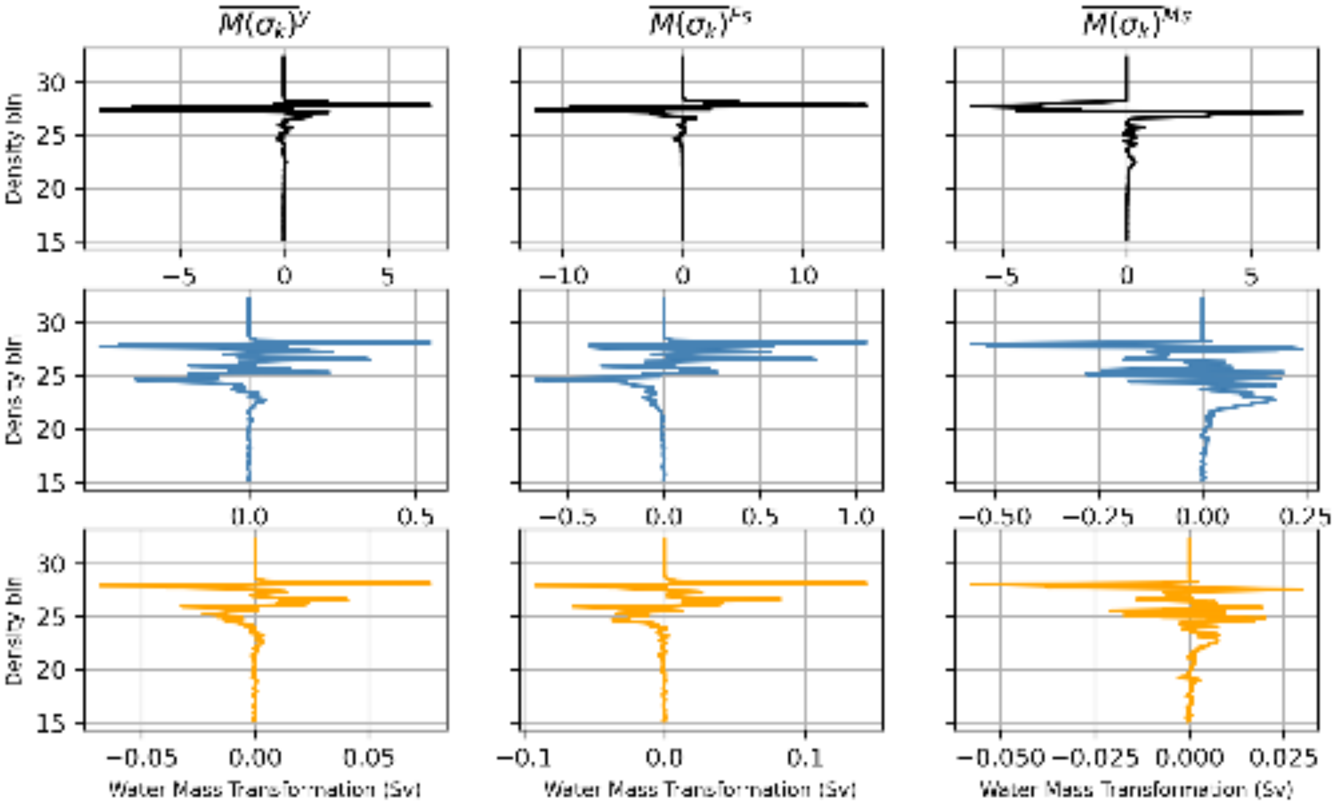
Yearly average ➡ $$\overline{M(\sigma_k)} = -\left[\overline{\Omega(\sigma_{k+1})} - \overline{\Omega(\sigma_k)}\right]$$

- Freezing season:
  - Water masses between 25-28 kg/m^3 sink likely due brine rejection.
- Melting season:
  - Water masses between 22-25 kg/m^3 rise.

Arctic ocean

Pack Ice

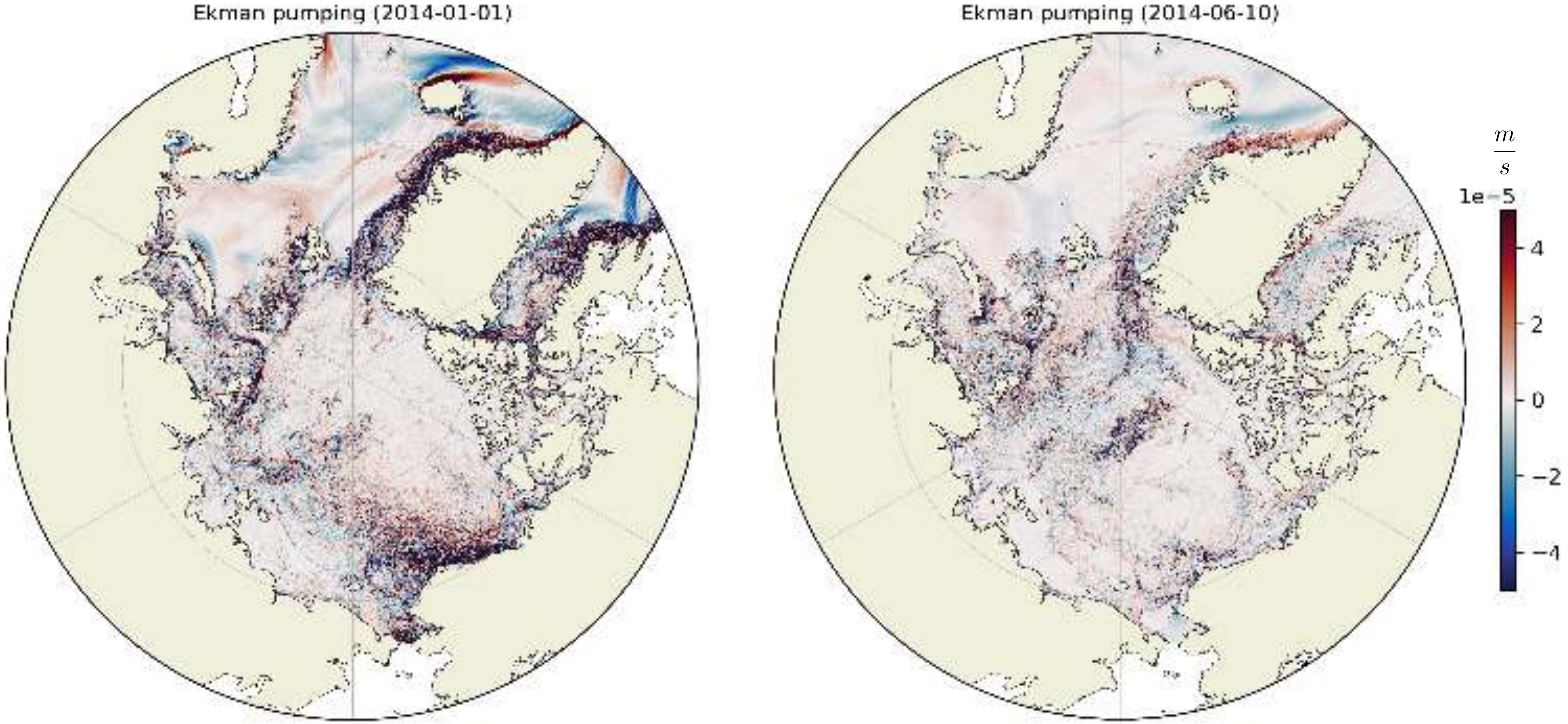
LKF ice



Positive formation rate = Water convergence (Downwelling)
Negative formation rate = Water divergence (Upwelling)

Ekman pumping

$$W_E = \frac{1}{\rho f}\left(\frac{\partial \tau_w^y}{\partial x} - \frac{\partial \tau_w^x}{\partial y}\right) + \frac{\beta}{\rho f^2}\tau_w^x$$



Ekman pumping

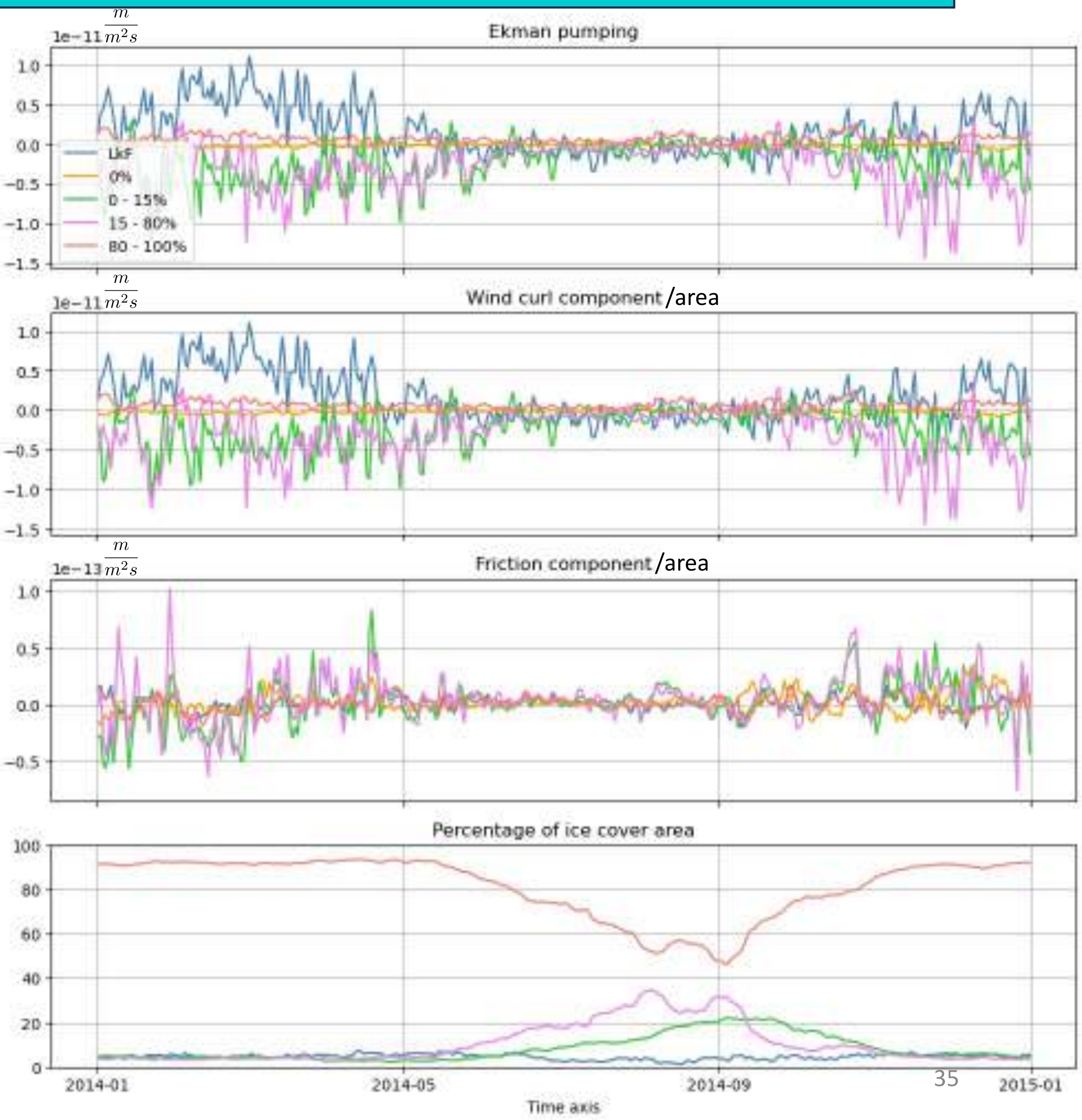
$$W_E = \frac{1}{\rho f}\left(\frac{\partial \tau_w^y}{\partial x} - \frac{\partial \tau_w^x}{\partial y}\right) + \frac{\beta}{\rho f^2}\tau_w^x$$

Downward Velocity = Ekman Pumping (downwelling)

Upward Velocity = Ekman Suction (upwelling)

- Seasonal cycle in the Ekman pumping, likely to the wind stress seasonal cycle.

- LKFs have a positive velocity, thus we expect upwelling
- Ekman pumping through LKF are comparable but opposite to the Ekman pumping through the ice pack



Take home messages

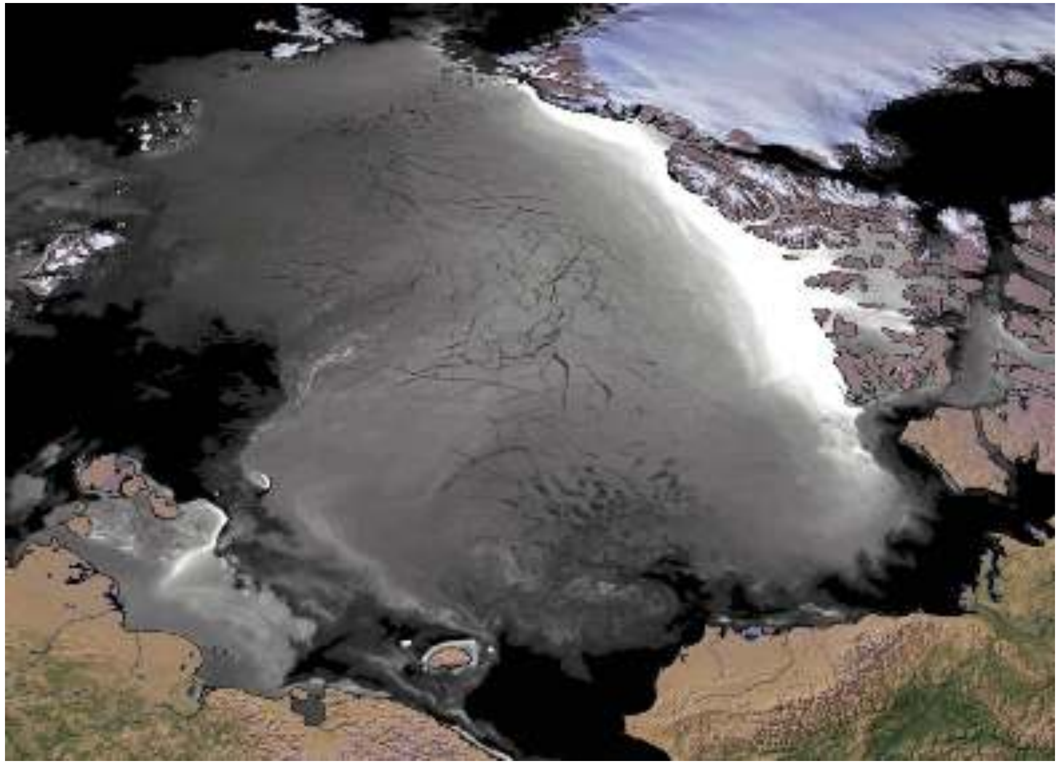
- LKFs cover less than 5% of the Arctic pack ice.
- Despite the small area cover:
  - The buoyancy fluxes are 20 or 30% larger than those in the pack ice.
  - LKF explain approximately 10% of the water mass transformation underneath the pack ice.
  - Ekman pumping in LKF is more than 2 times larger than in the pack ice.

Conclusions

- Eddies and LKFs in the Arctic showcase the importance of ocean-sea ice-atmosphere interactions

  (not well represented in state-of-the-art models).

- Evidence that ocean eddies make the sea-ice heterogeneous and likely make the sea-ice more brittle.
- LKF are open window between the ocean and the atmosphere.
  - Strong evidence that LKF are capable to modify the ocean properties.



Thanks!

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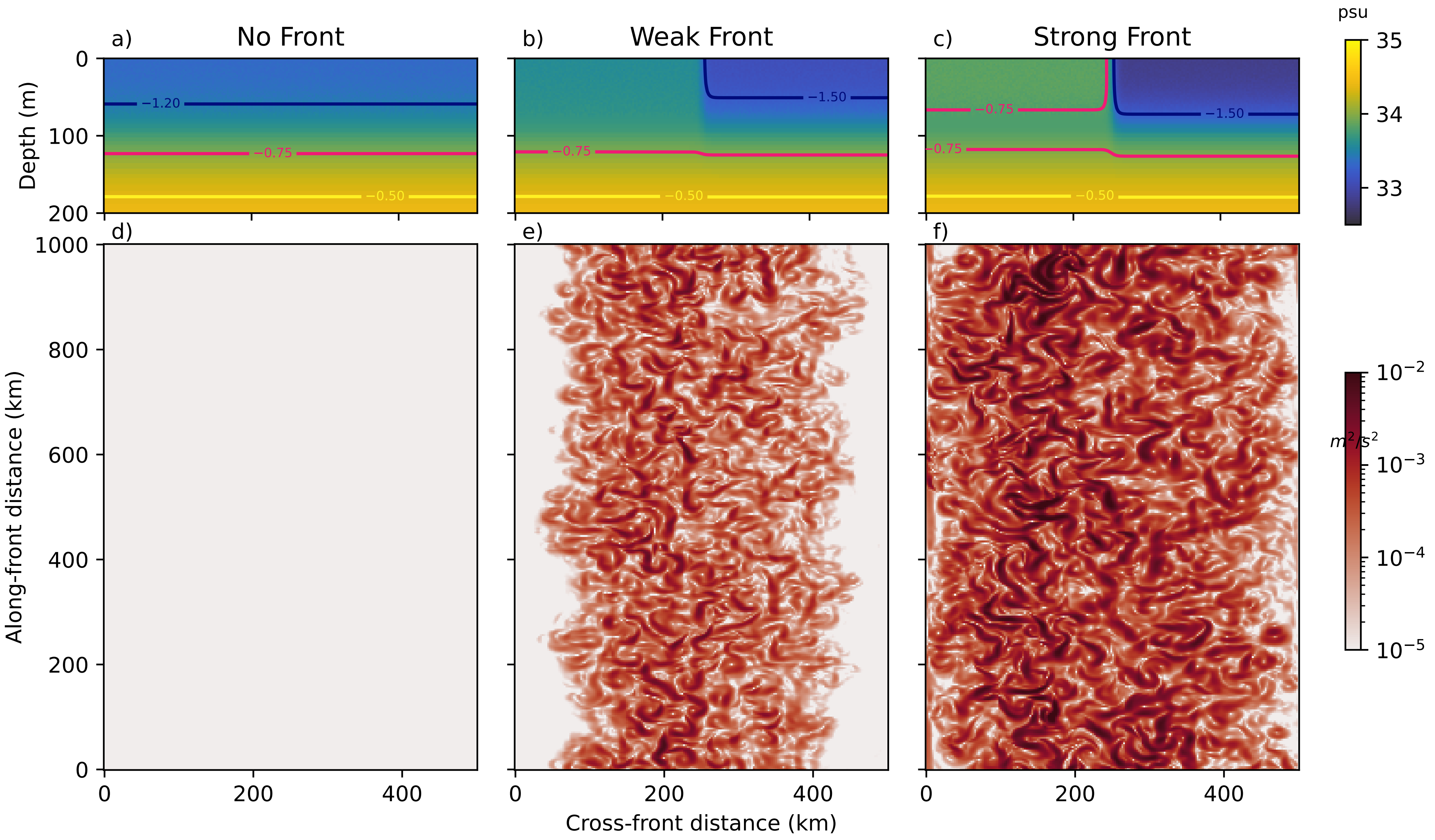
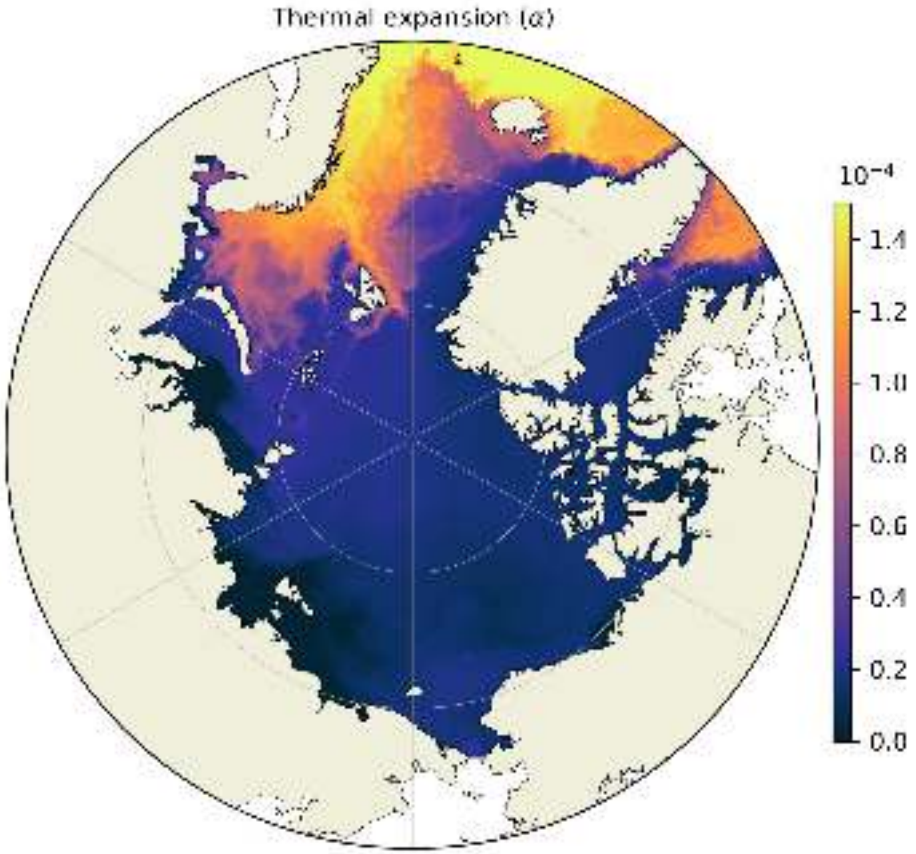
I will be at NOC until tomorrow evening if you would like to talk with me!

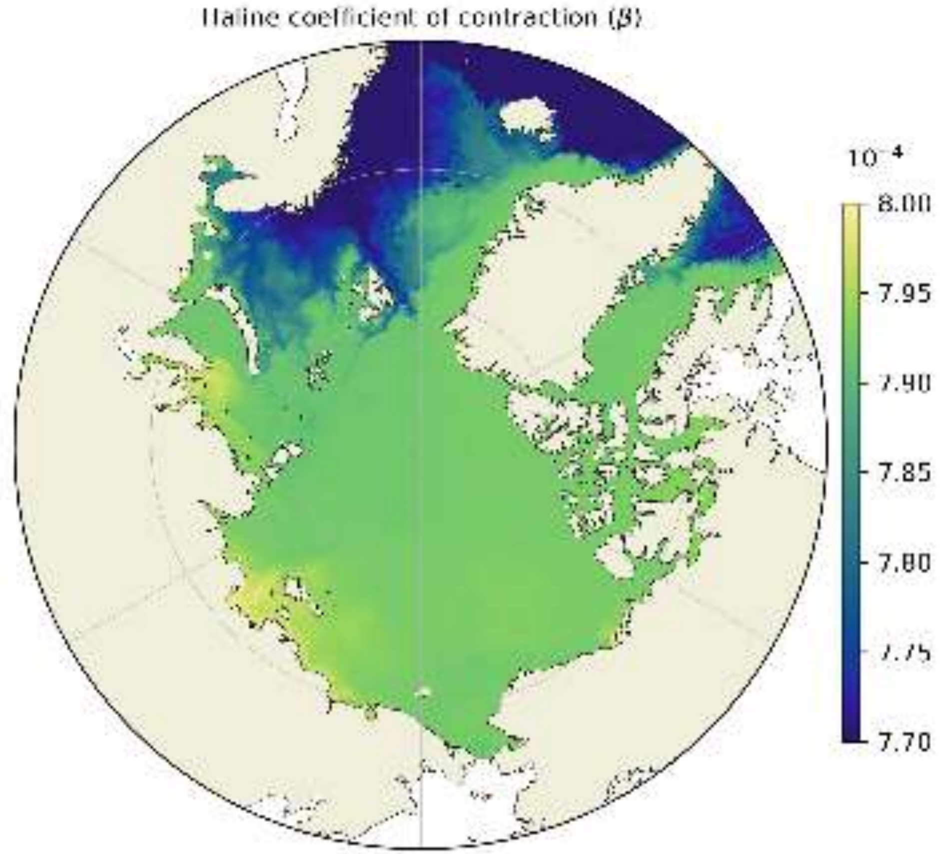


a)
No Front
b)
Weak Front
c)
Strong Front
psu
35
34
33
Depth (m)
0
100
200
−1.20
−0.75
−0.50
−1.50
d)
e)
f)
1000
800
600
400
200
0
Along-front distance (km)
0
200
400
Cross-front distance (km)
10^−2
10^−3
10^−4
10^−5
m^2/s^2

Arctic buoyancy budget (Heat vs Freshwater)



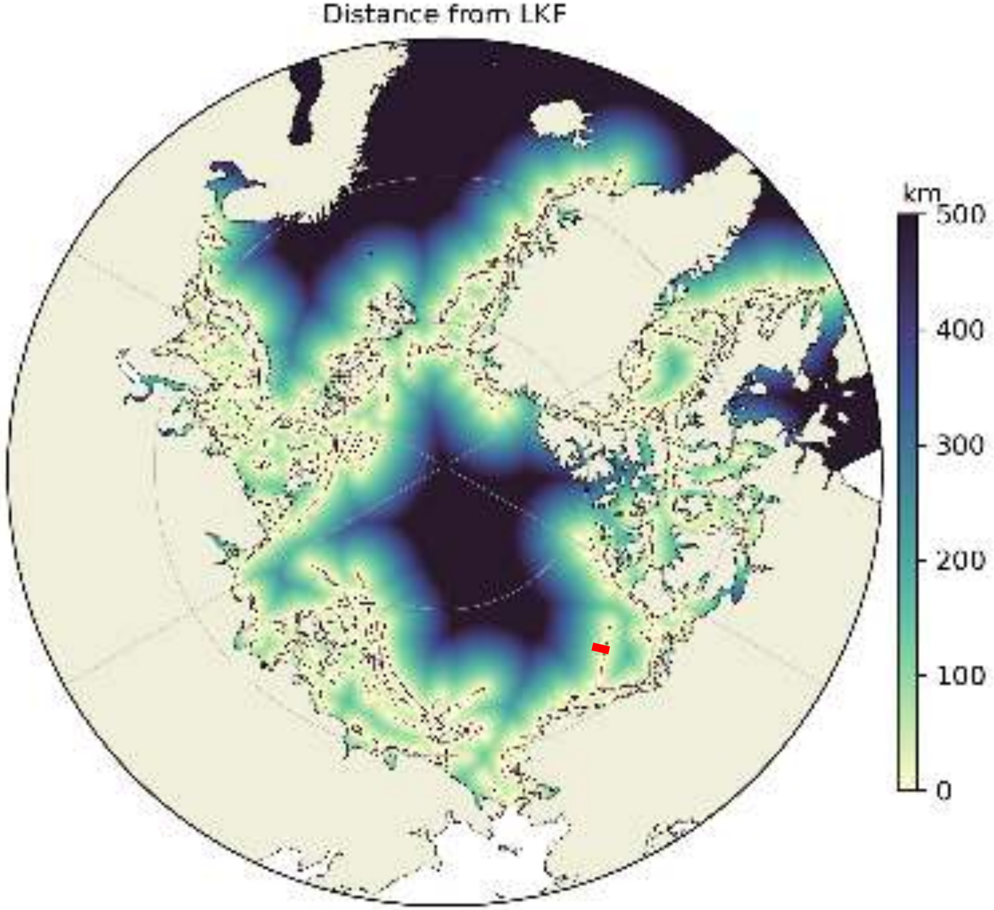
Important at “Relatively” low Latitudes



Important at “Relatively” high Latitudes

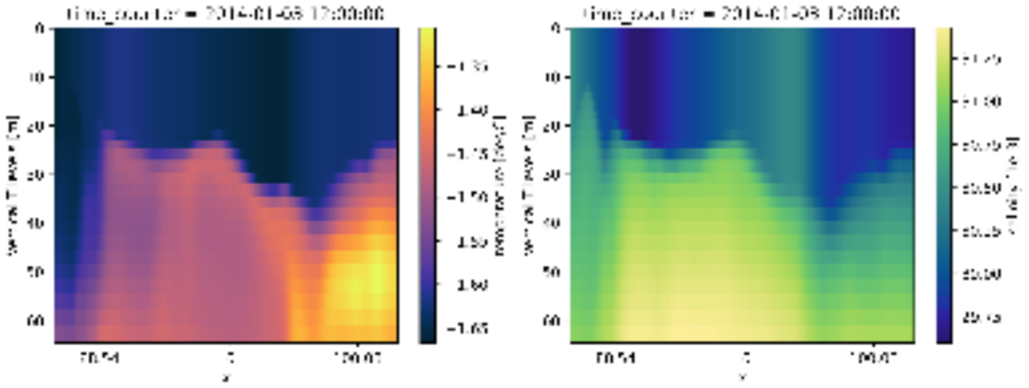
The Arctic is a β-Ocean

WIP: Lateral influence

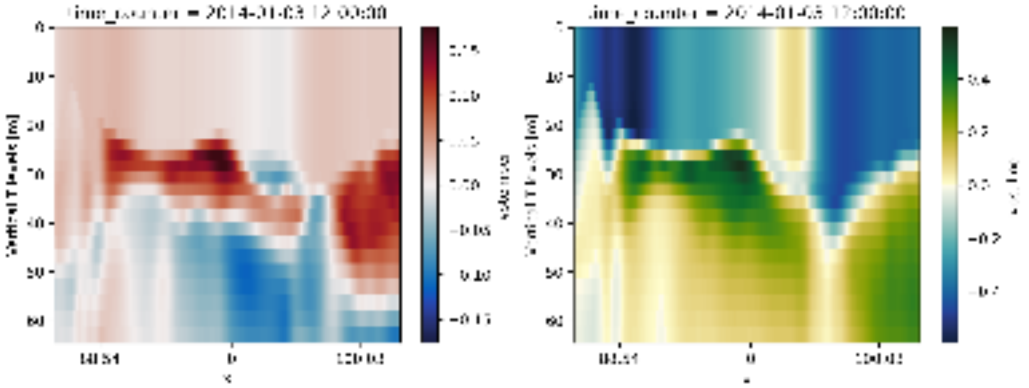


Temperature

Salinity



Anomalies from monthly mean



Salt and temp anomaly underneath the LKF