Ocean-sea ice interactions at decreasing scale and increasing resolution

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With contributions from
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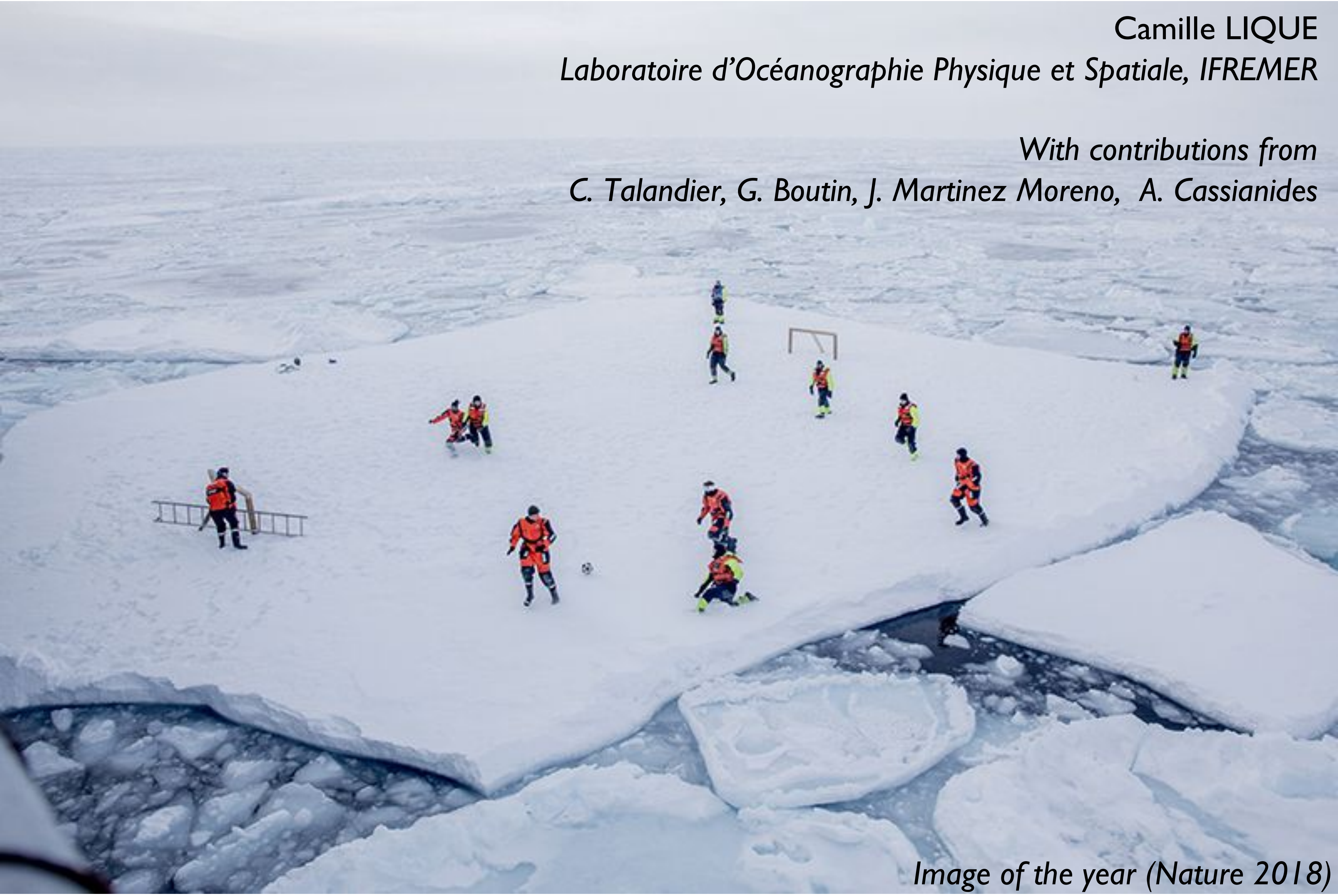
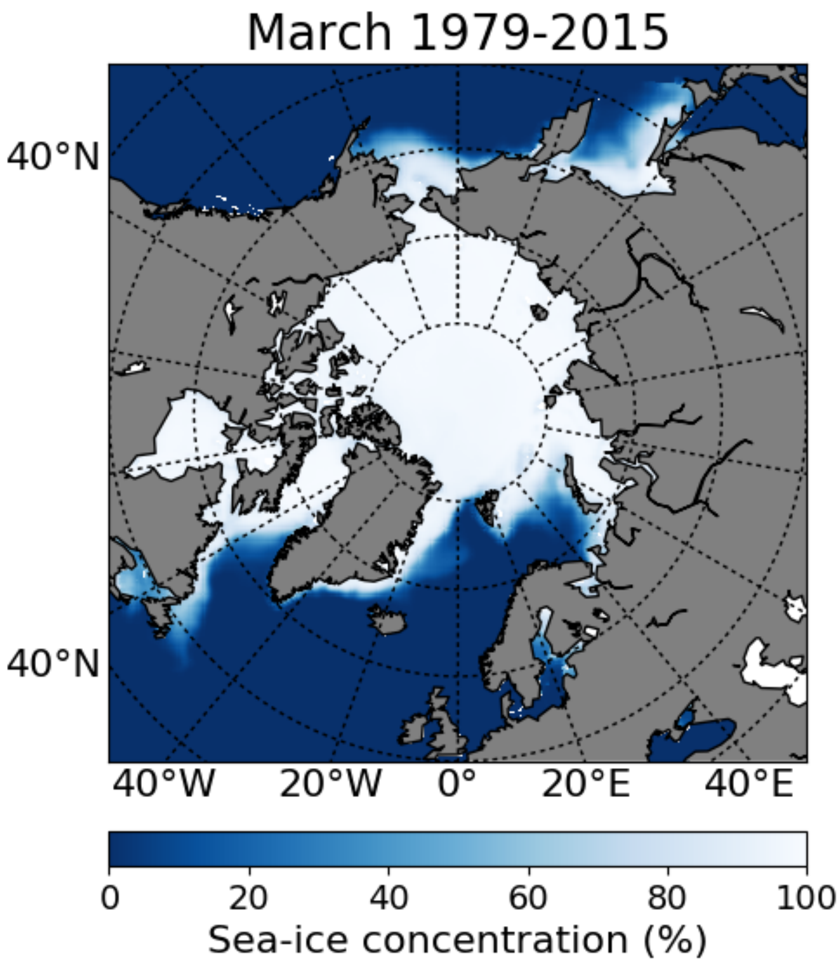
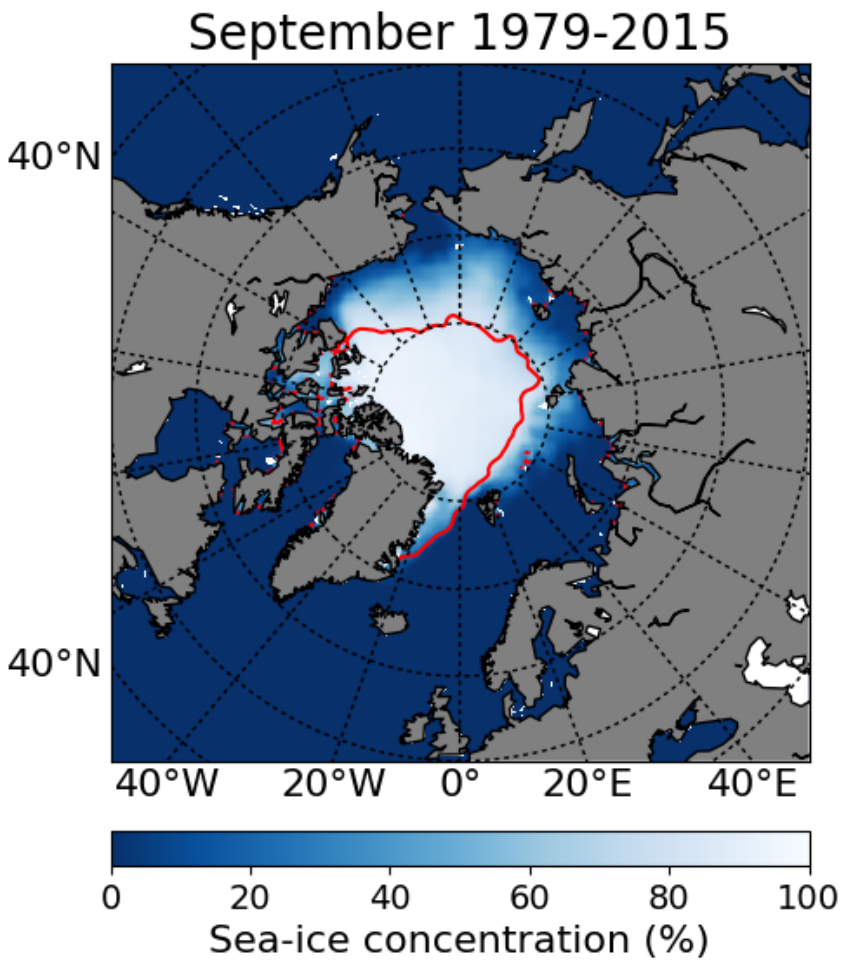


Image of the year (Nature 2018)

The picture at large scale and long timescale

- Sea ice exhibits a large seasonality

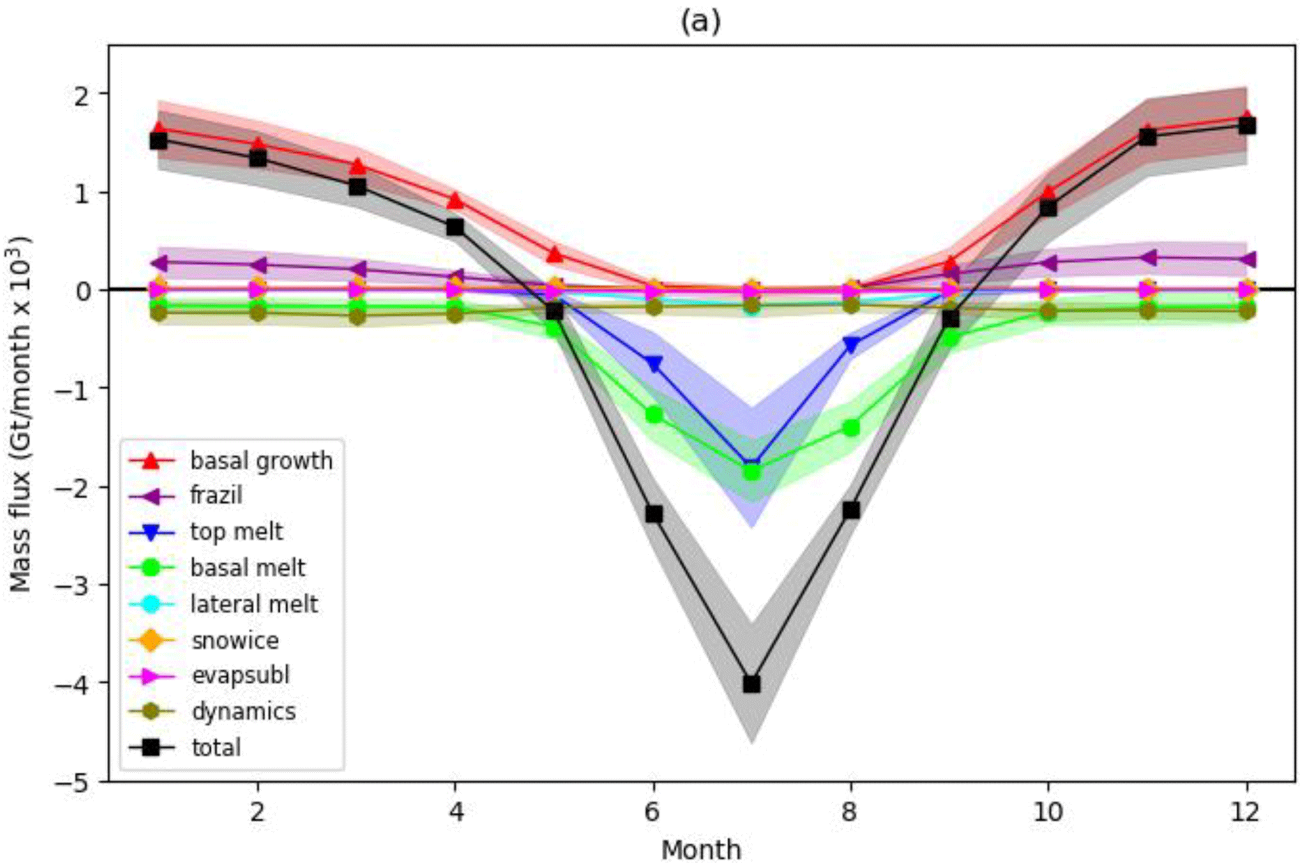




Observations from NSIDC

The picture at large scale and long timescale

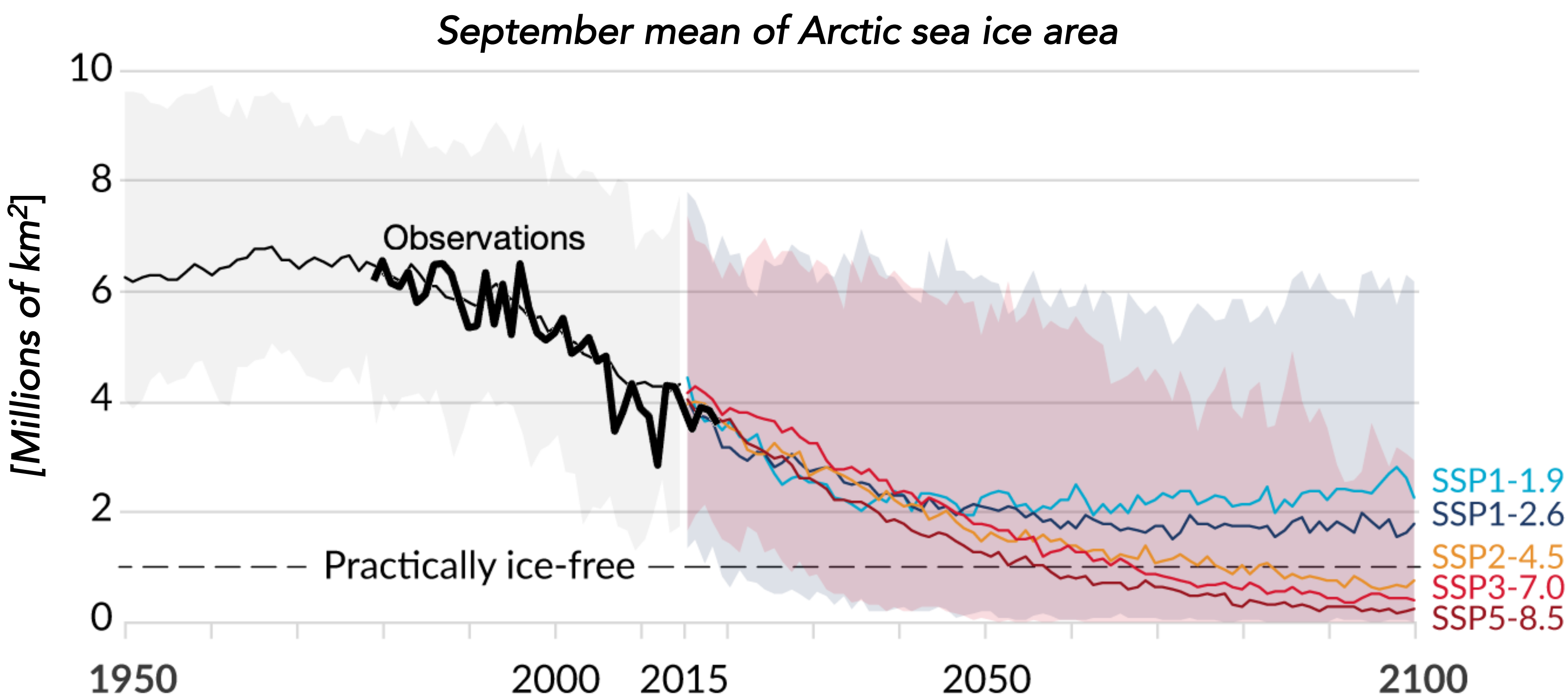
- Sea ice exhibits a large seasonality
  - > *Largely driven by thermodynamics*
  - > *ocean and atmophere drive ~50% of the melt (according to CMIP6 models)*



Data from CMIP6 (multi model mean), Keen et al. 2021

The picture at large scale and long timescale

- Sea ice exhibits a large seasonality
- And a long term trend, that will amplify in the future

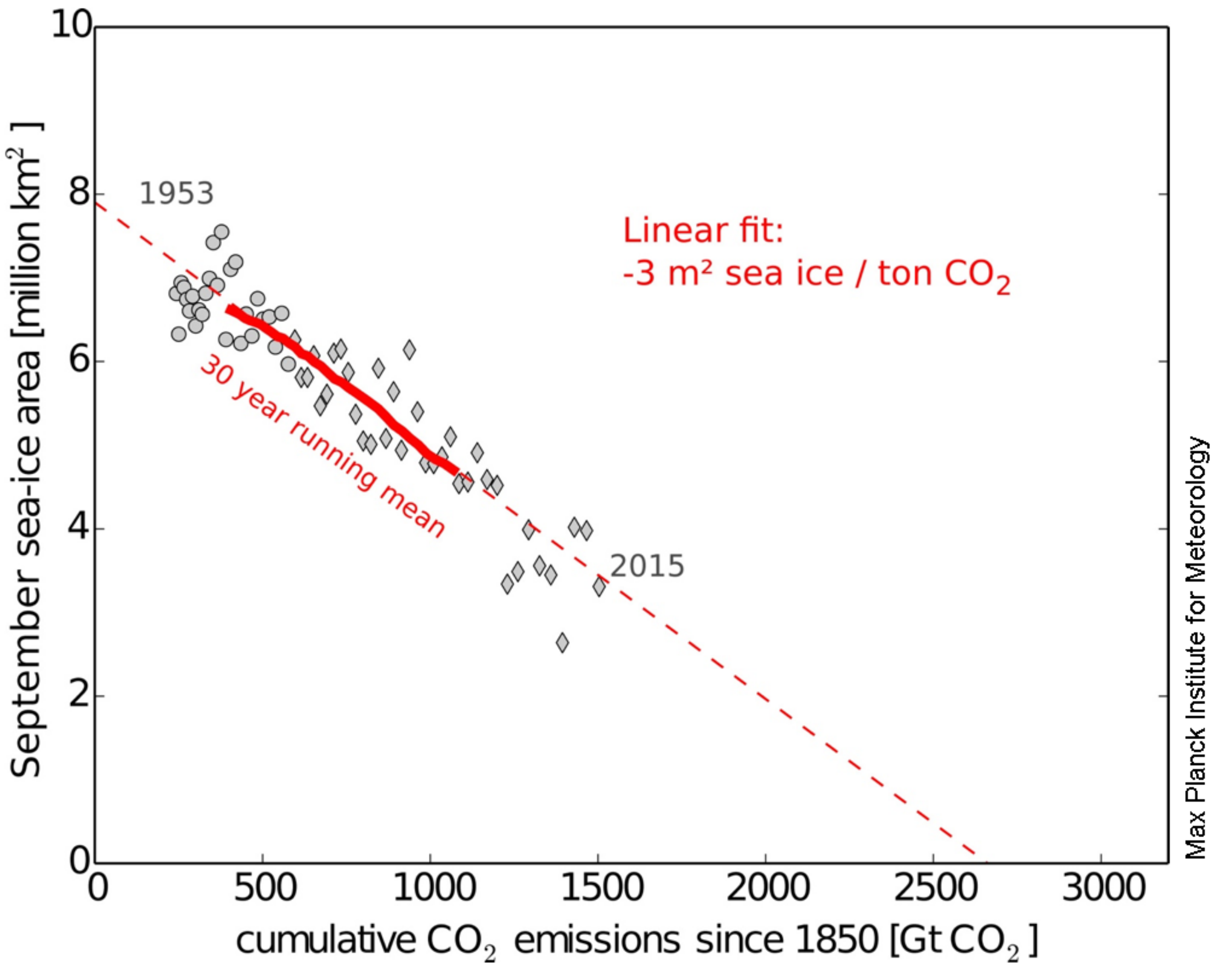


Observations from NSIDC, IPCC 2021

The picture at large scale and long timescale

- Sea ice exhibits a large seasonality
- And a long term trend, that will amplify in the future

  > *Overall a response to our anthropogenic CO_2 emissions*

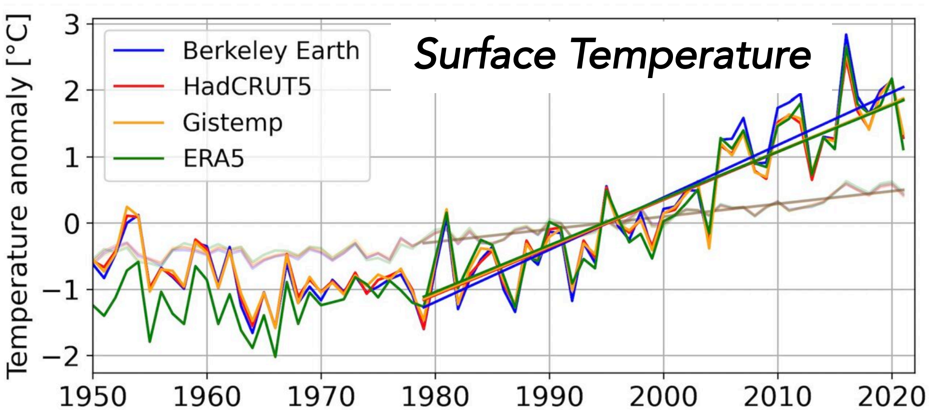


Adapted from Notz & Stroeve 2016

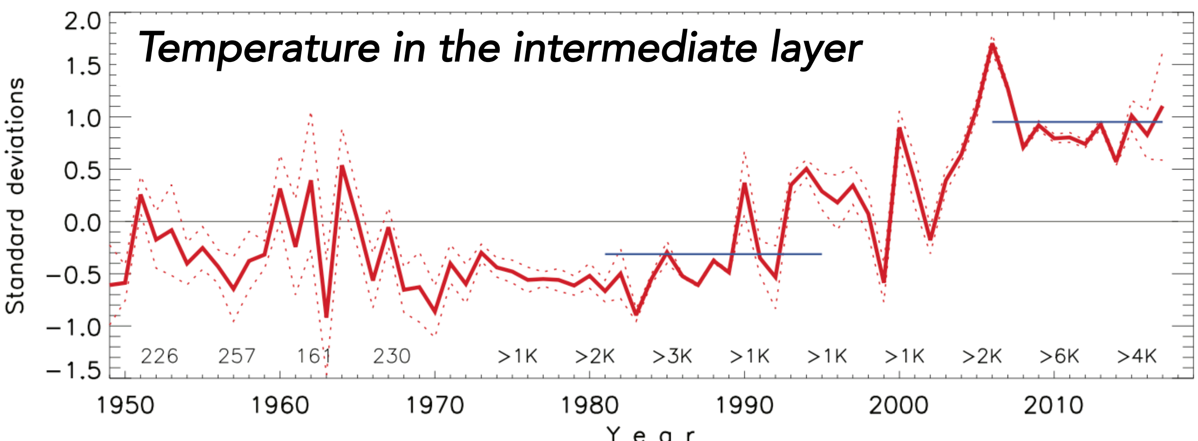
The picture at large scale and long timescale

- Sea ice exhibits a large seasonality
- And a long term trend, that will amplify in the future

> Overall a response to our anthropogenic CO_2 emissions, that manifests locally as a warming of both the ocean and the atmosphere



The atmosphere is warming 4 times faster than the rest of Earth



All the layers of the ocean are warming, in response to the atmosphere and/or changes in advection

Rantanen et al. 2022; Polyakov et al. 2020

But in reality, various scales can be seen in sea ice

Pictures taken between Svalbard and the North Pole in September 2021

Caveats from the picture at large scale and long timescale

- Climate models are not capturing the heterogeneity in sea ice nor the complexity of the interactions between the ocean, sea ice and atmosphere

  > *The Rossby Radius in the Arctic is ~10km in the interior and ~1km on the shelves*

  > *Large non-linearity arises from the interactions with sea ice*

- In the rest of this talk, I will present a few examples illustrating interactions at small scales

  > *Surface front*

  > *Mesoscale eddies*

  > *Linear Kinematic Features (LKF)*

  > *Surface waves*

- … and I ll try to discuss their potential importance for the large scale picture

Not a review – examples mostly from my own work (hence the Arctic focus)

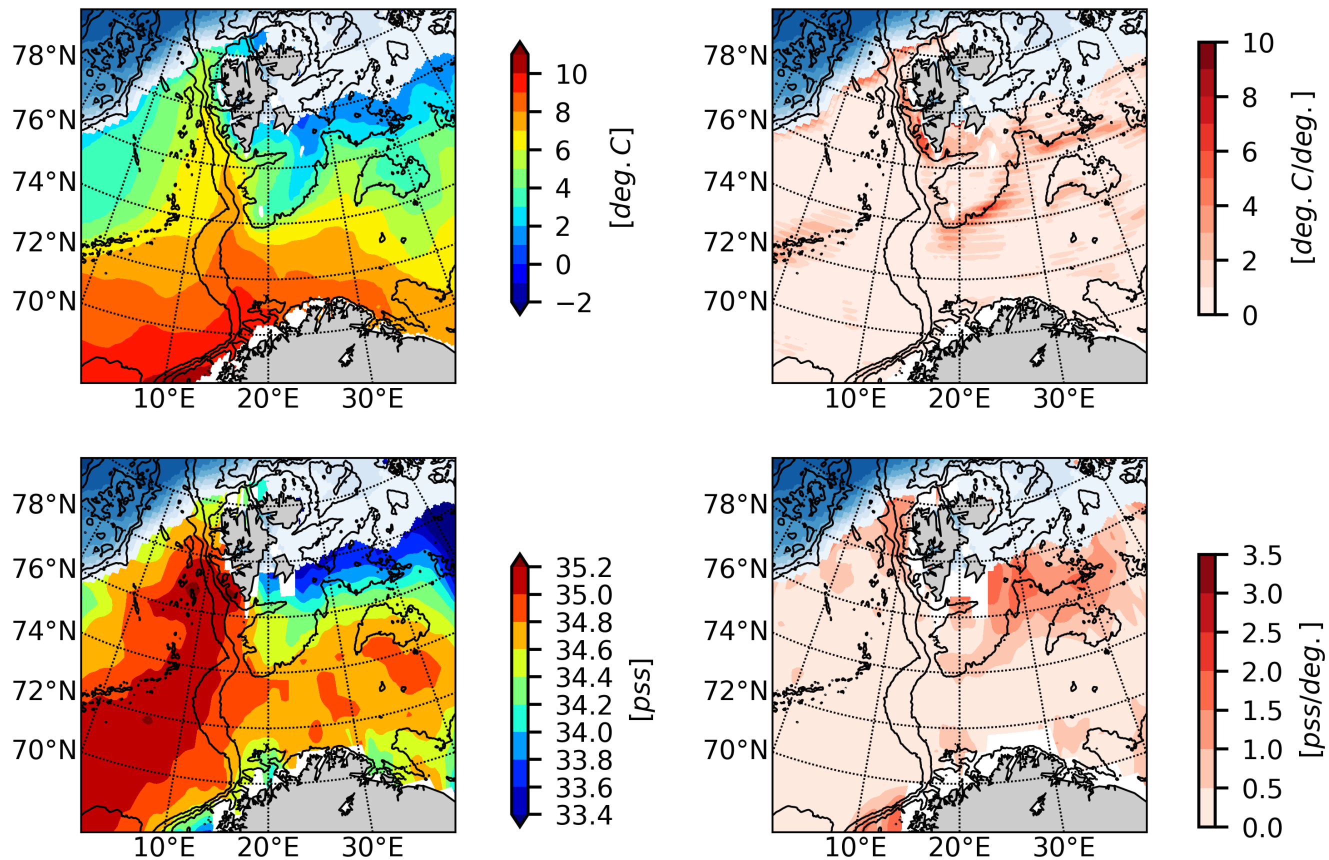
Focus on the processes and how we look at them

Ocean front can constrain sea ice

- In the Marginal Ice Zone, strong fronts in temperature and salinity are commonly observed
- The example of the Barents Sea: The Polar Front

SST from OSTIA

SSS from SMOS



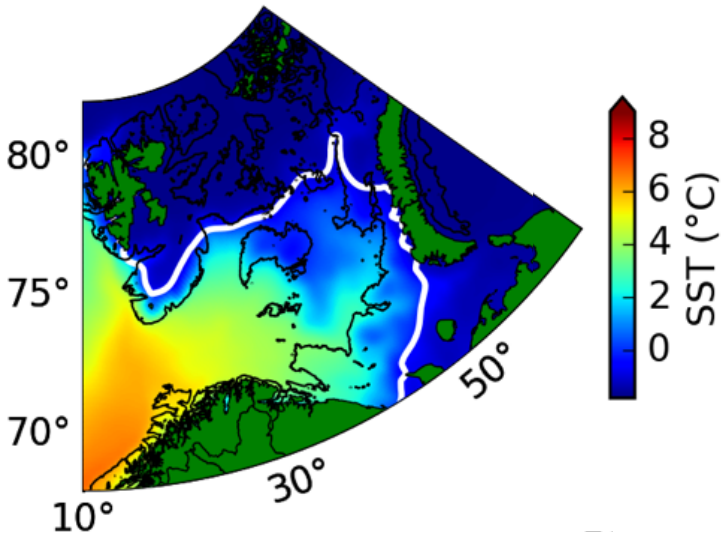
Courtesy of N. Kolodziejczyk

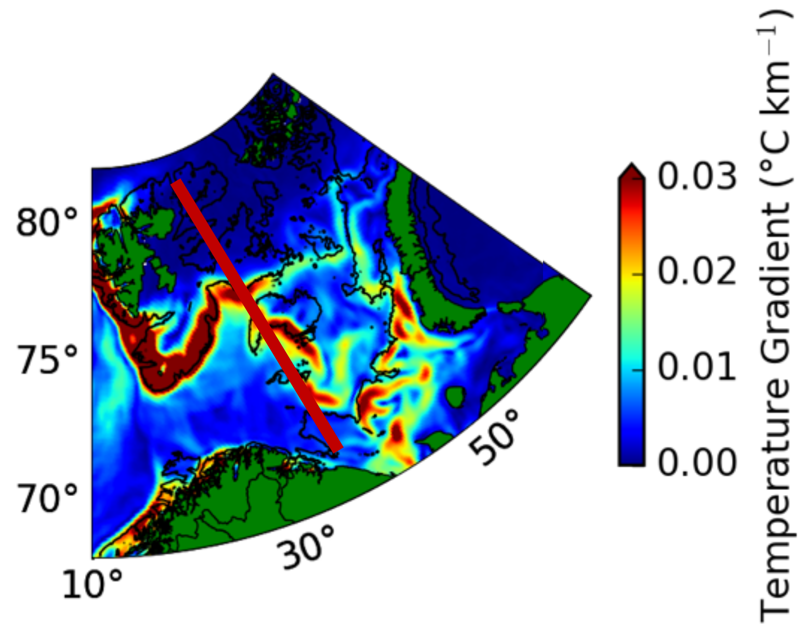
Ocean front can constrain sea ice

- Detection of the Polar Front from SST (*HR OSTIA dataset; Donlon et al. 2012*)
- The front is fixed to the ~220m isobath

  > *corresponds to a shelf slope current constrained by potential vorticity*

Winter mean 2005-2017
+ sea ice edge





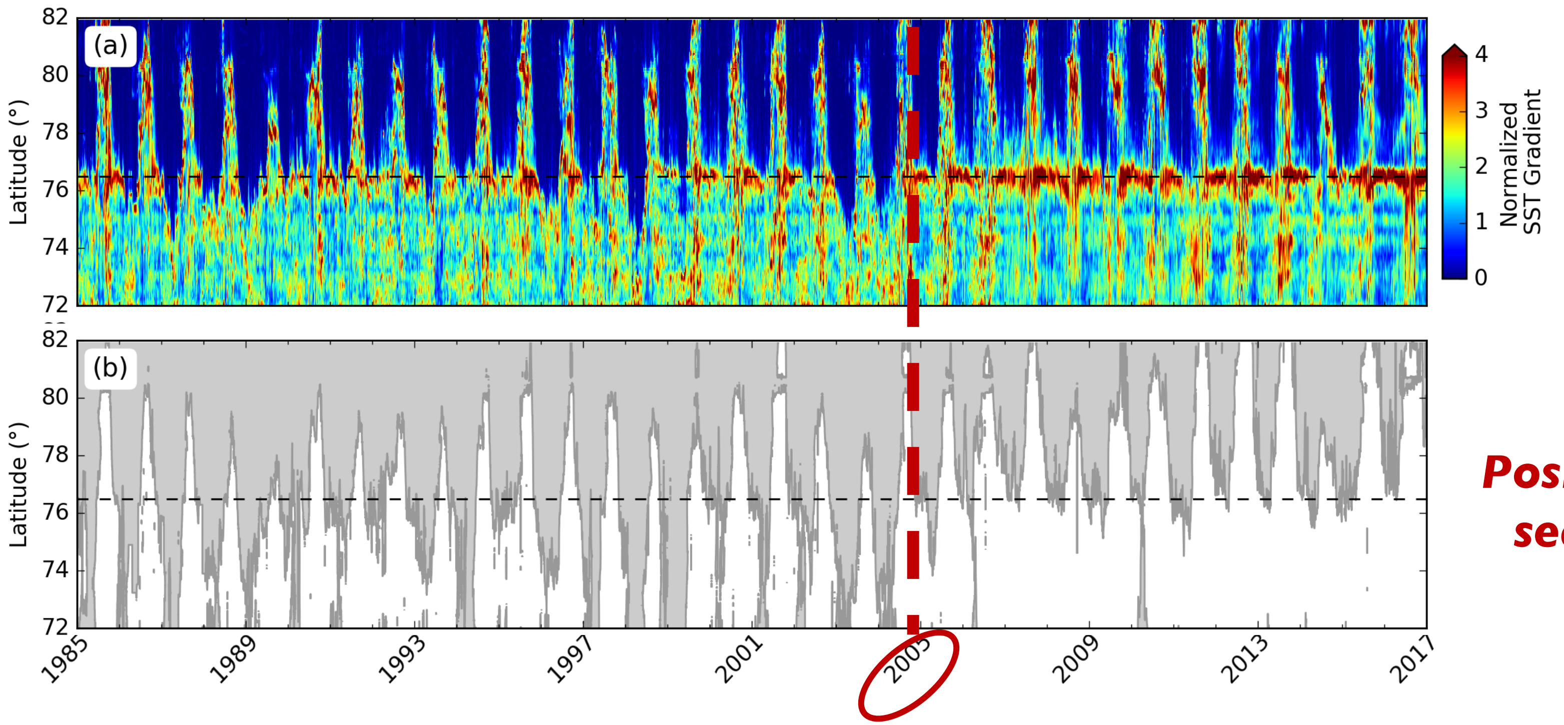
Barton et al. 2018

Ocean front can constrain sea ice

Regime shift in 2005!

> *Intensification of the SST gradient*

> *winter sea ice expansion limited by the Polar Front*

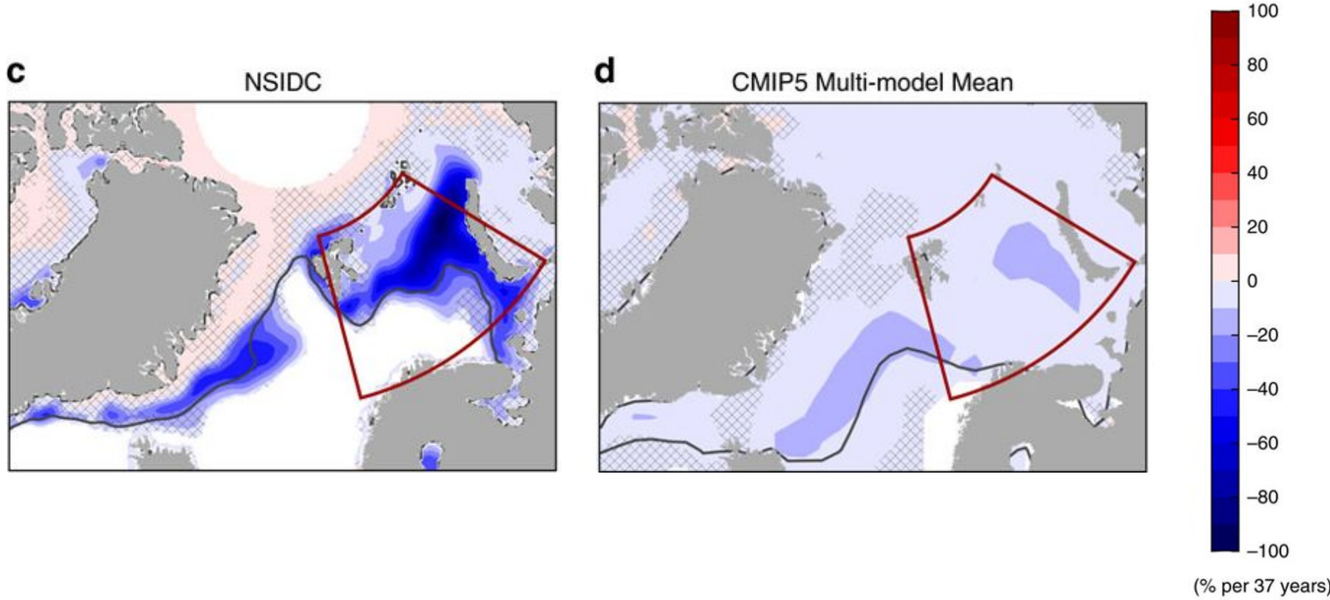


Position of the sea ice edge

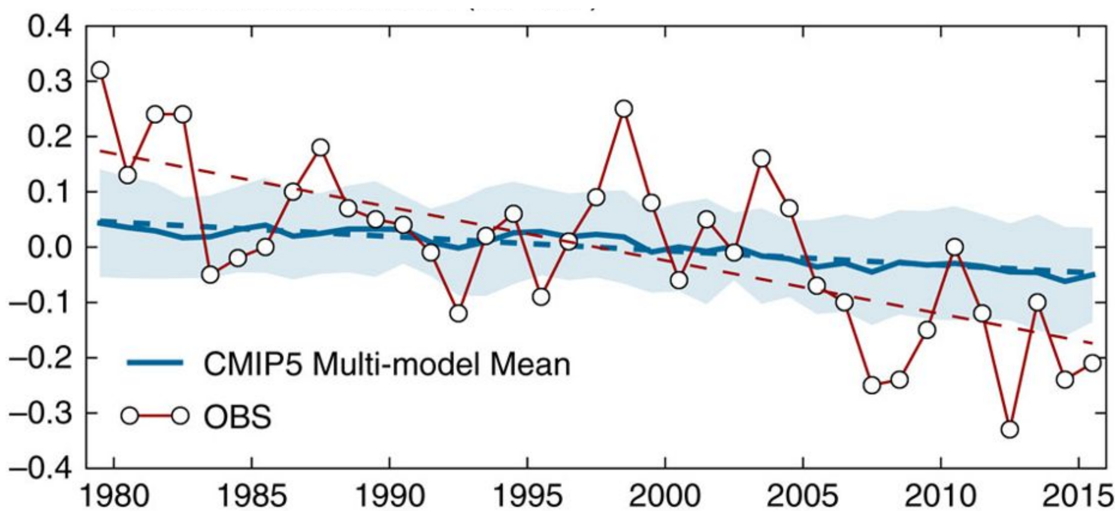
Barton et al. 2018

Ocean front can constrain sea ice

Winter sea ice retreat in the Barents Sea from CMIP5 models:



March SIC trend over 1979–2015.



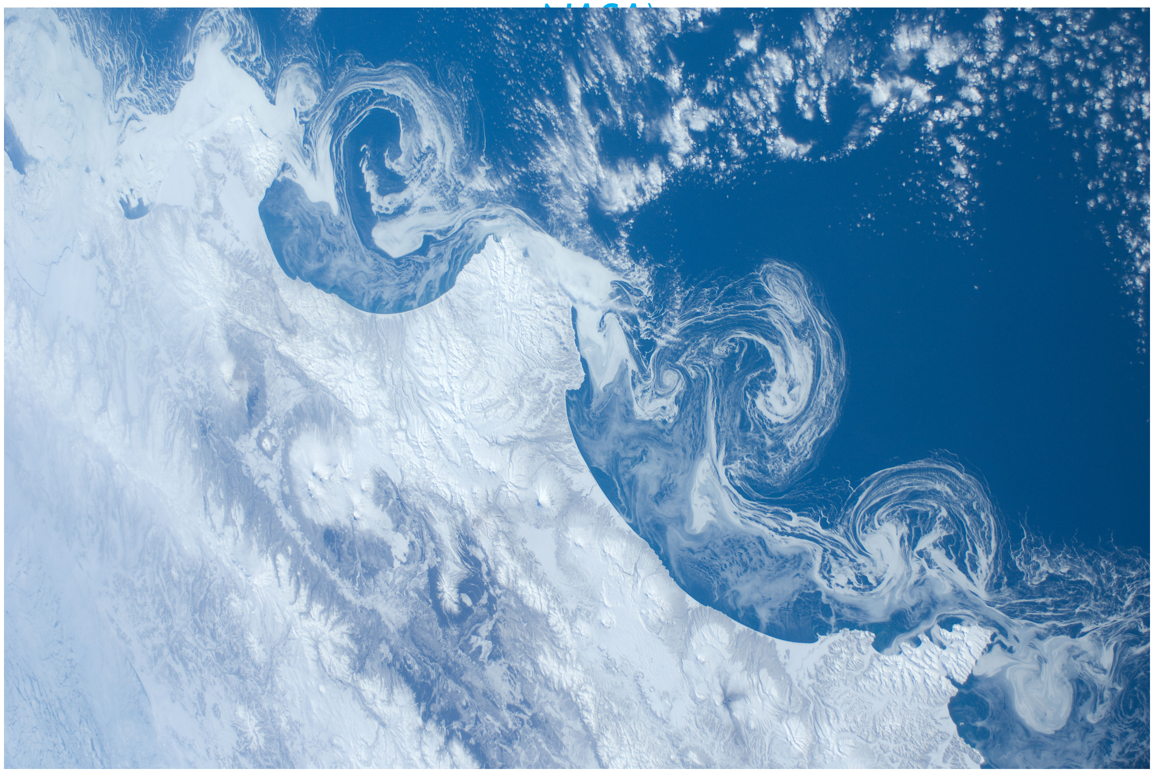
March extent in the Barents Sea

Li et al. 2017

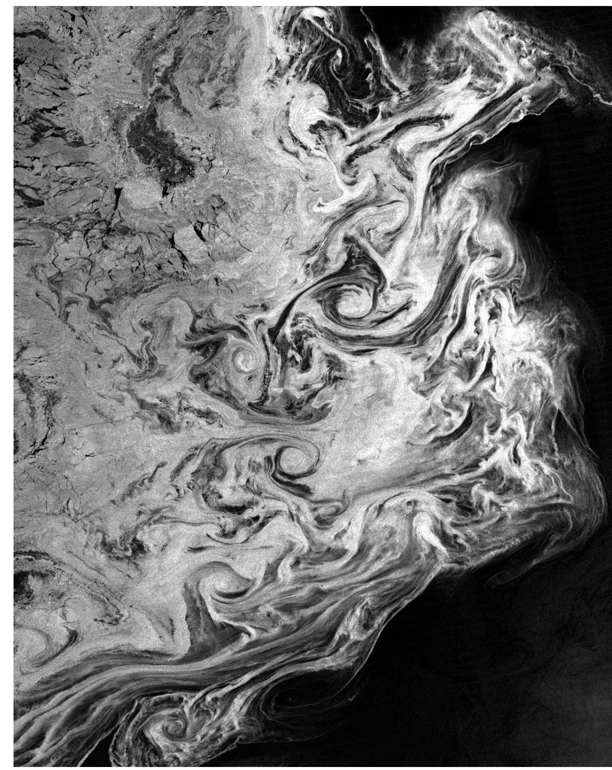
Interaction between eddy and sea ice

- The typical signature of ocean eddies and filaments is visible in sea ice

Picture taken form the ISS, March 2012 (credit: NASA)

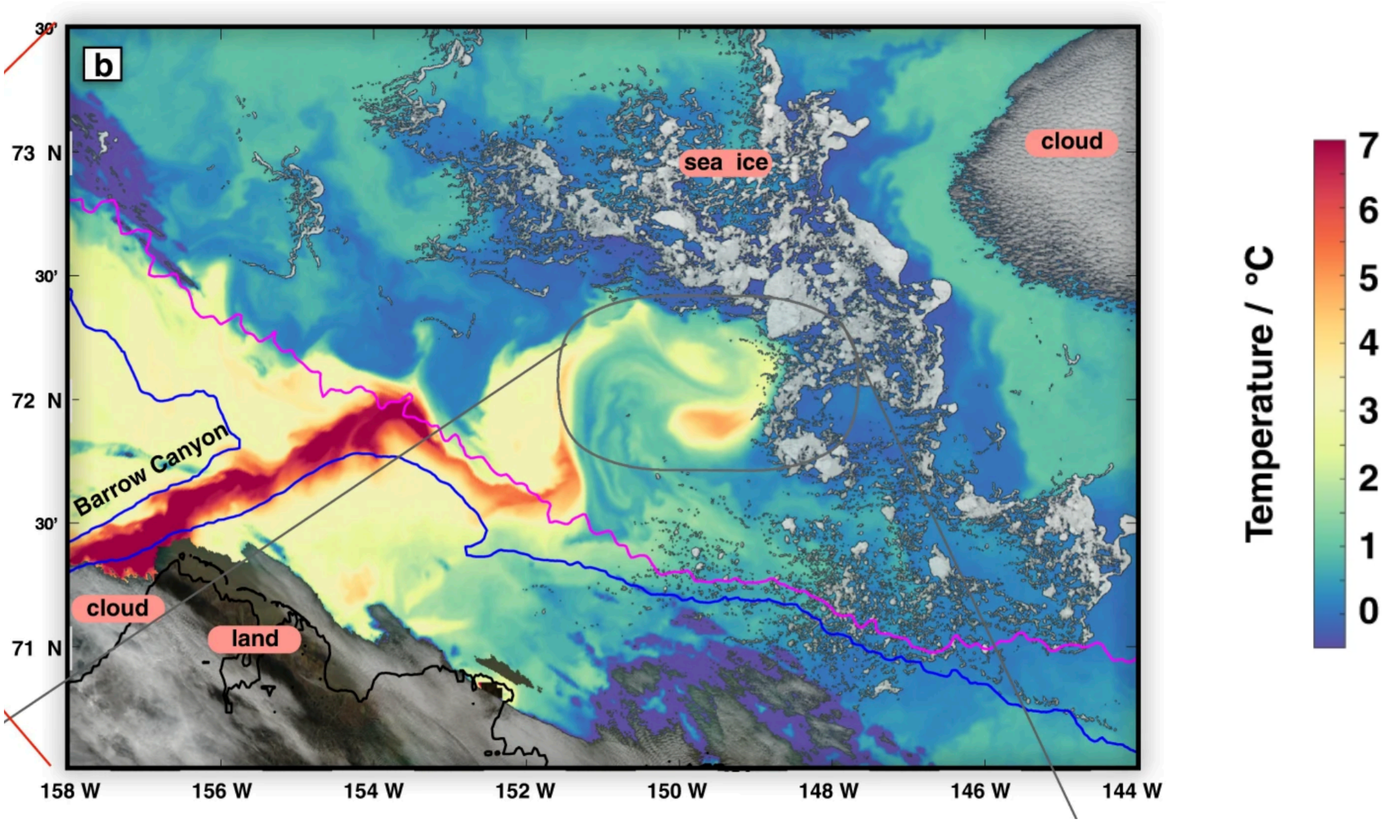


Sentinel 1A SAR,
Beaufort Sea, Sept. 2015



Interaction between eddy and sea ice

- The typical signature of ocean eddies and filaments is visible in sea ice
- Observations and idealized models have suggested that heat flux within eddies can enheance sea ice melt

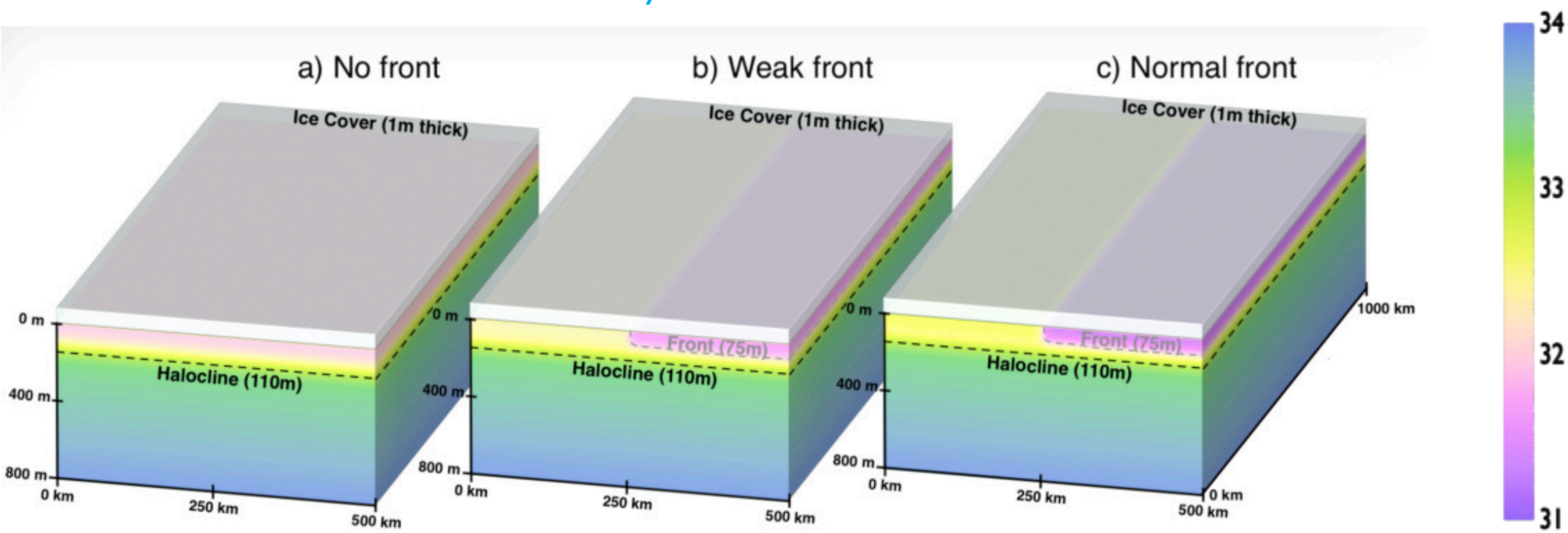


MacKinnon et al. 2021

Eddy driven heterogeneity in sea ice

- We consider a ‘shoe box’ at high resolution representative of the marginal ice zone
- Forcing = a mean seasonal cycle of the heat flux (no wind)
- 3 cases, with different intensity of the front and hence of the mesoscale field
- Focus on the sea ice formation stage

Salinity - Initial conditions



Martinez-Moreno et al. subm

Eddy driven heterogeneity in sea ice

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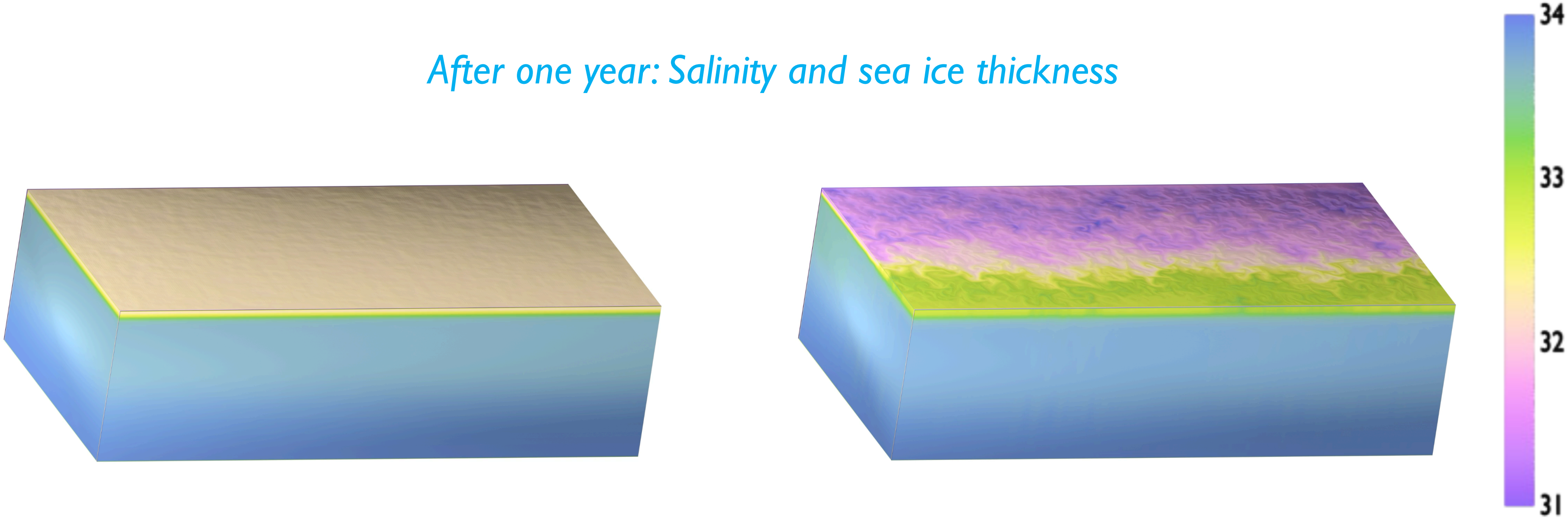
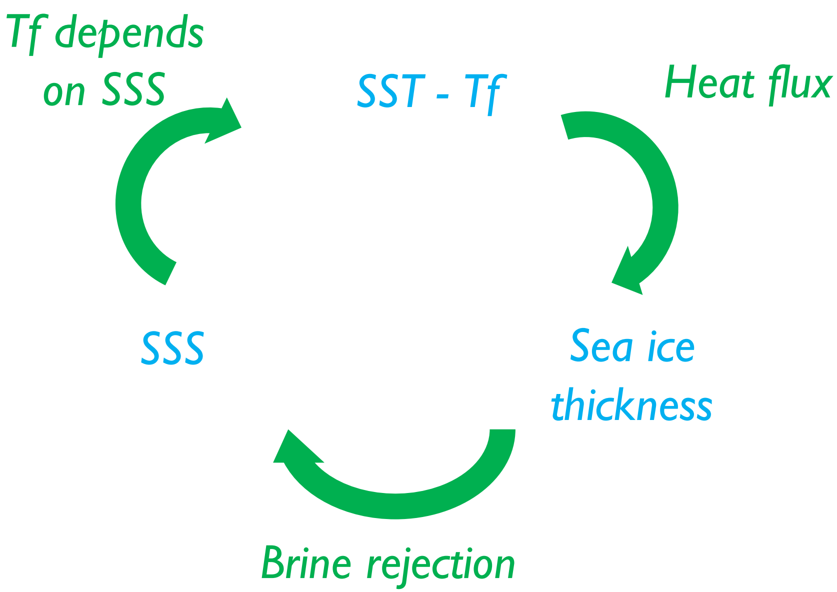
After one year: Salinity and sea ice thickness

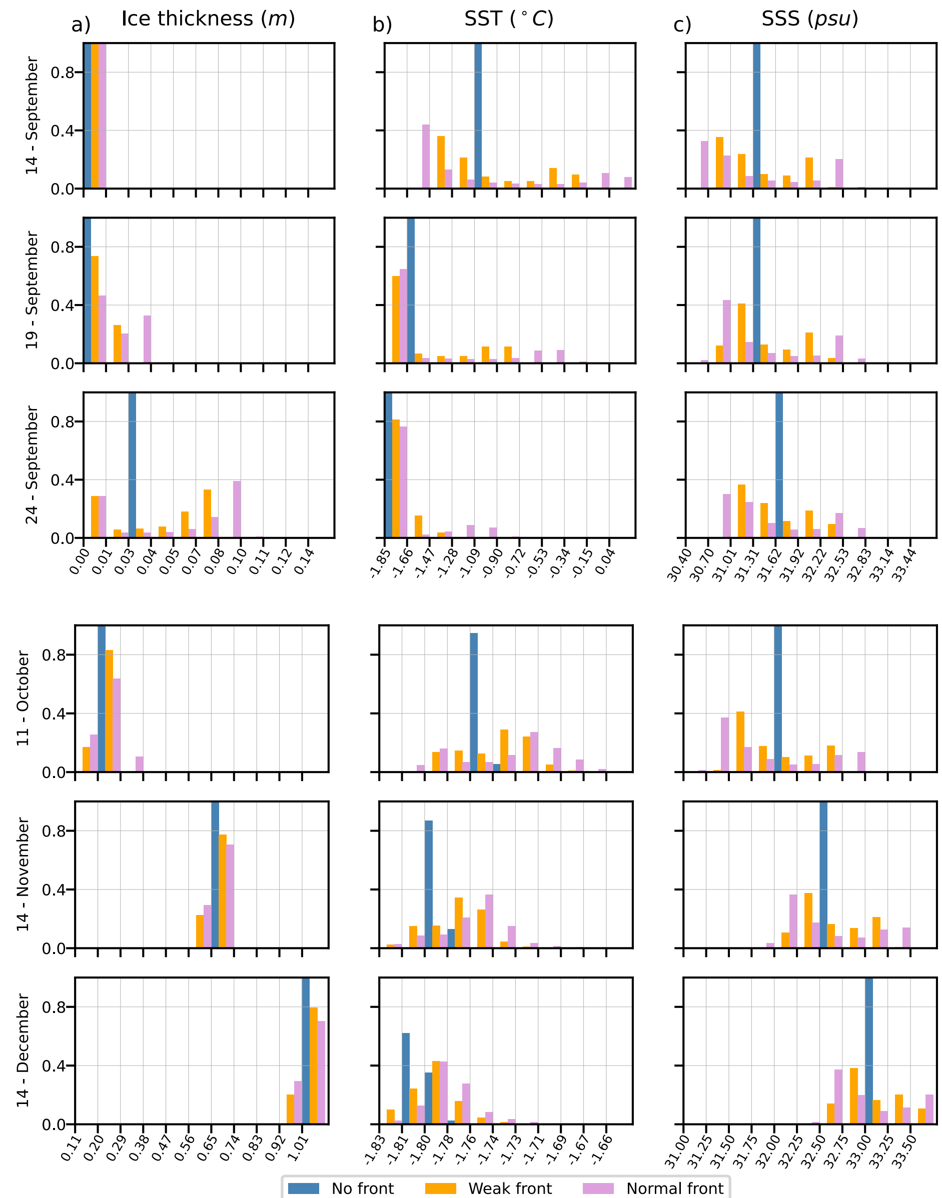


Martinez-Moreno et al. subm

Eddy driven heterogeneity in sea ice

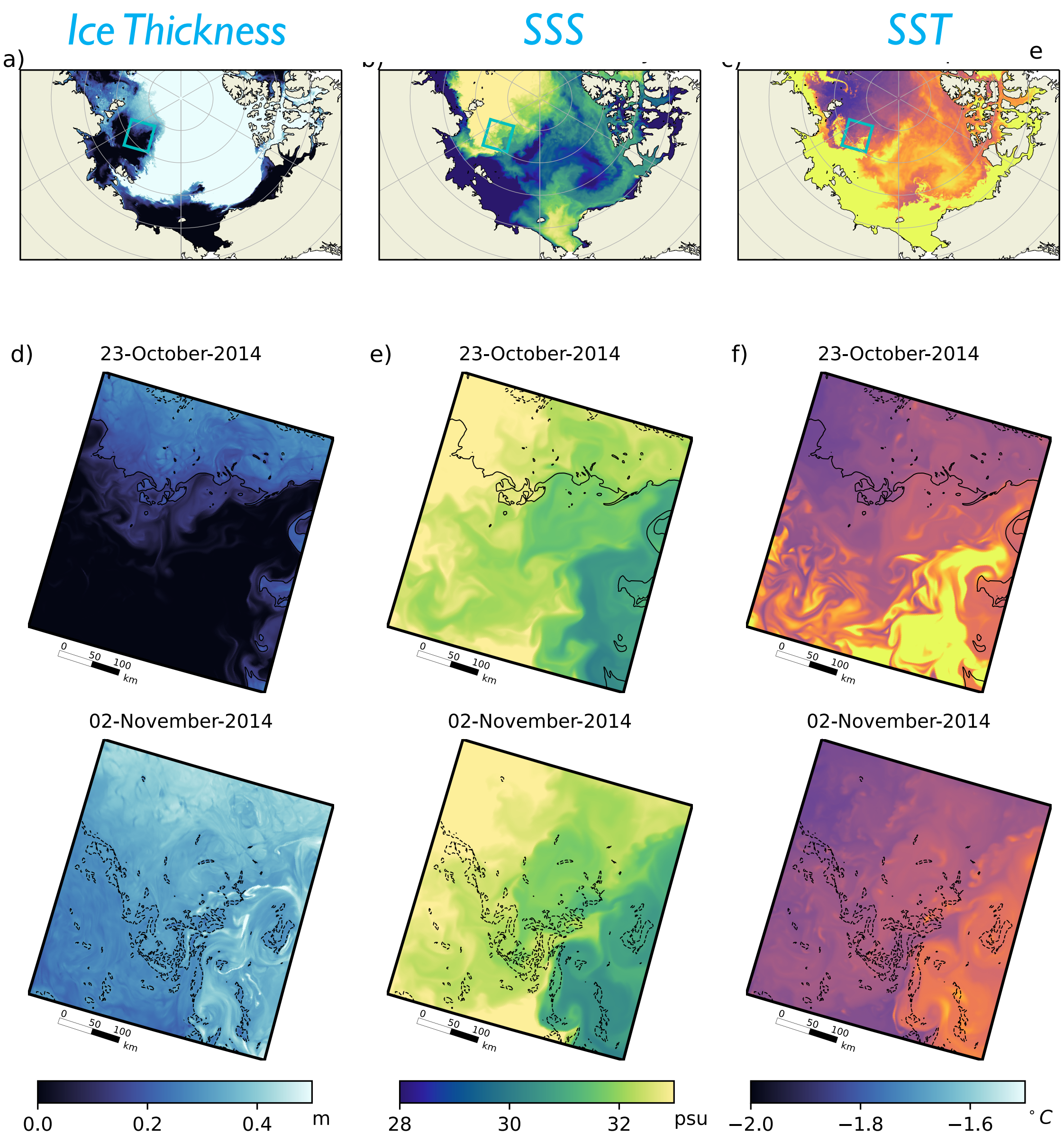
- In the presence of eddies, we see herogeneity in sea ice thickness, that lasts for at least a few months





Martinez-Moreno et al. subm

Eddy driven heterogeneity in sea ice

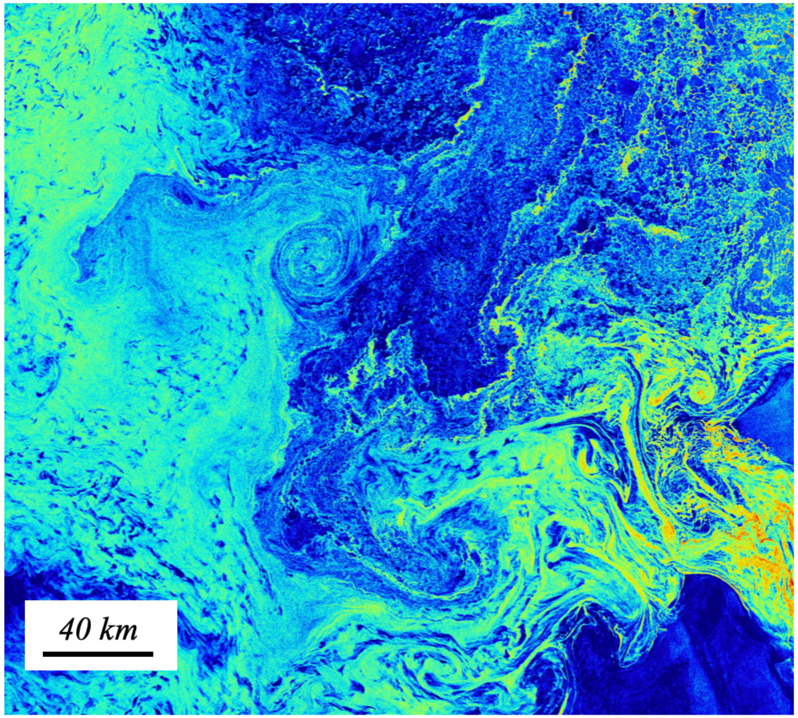


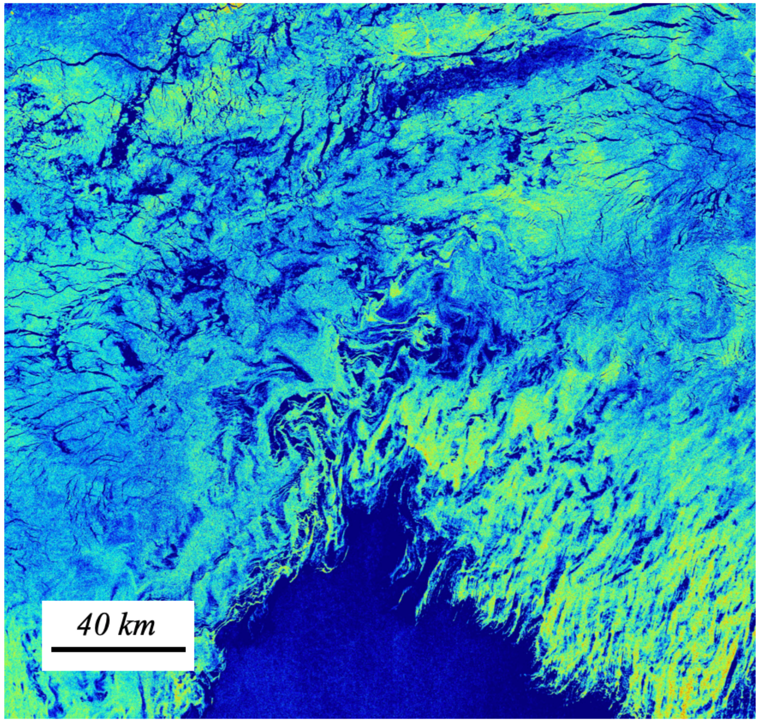
- The same mechanism appears to be at play in realistic simulation at very high resolution
- If heterogeneity lasts, it will likely affect the future evolution of sea ice

Data from SEDNA @800m resolution; Martinez-Moreno et al. subm

Eddy signature in sea ice motion

- SAR images (at high resolution) are very helpful to detect eddy visually
- … but more can be done to detect eddy!



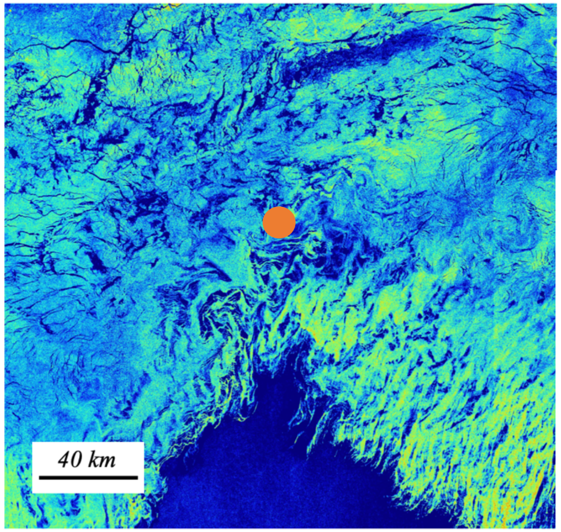


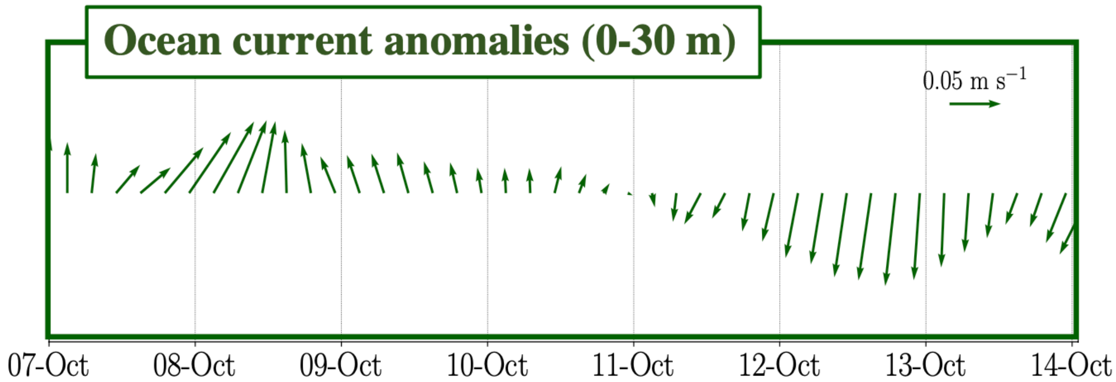
SAR images in the Canadian Basin

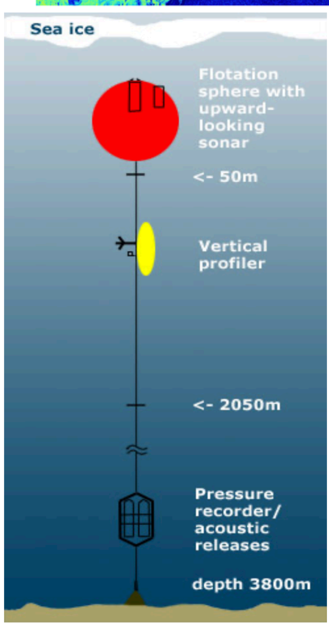
Cassianides, Lique & Korosov 2021

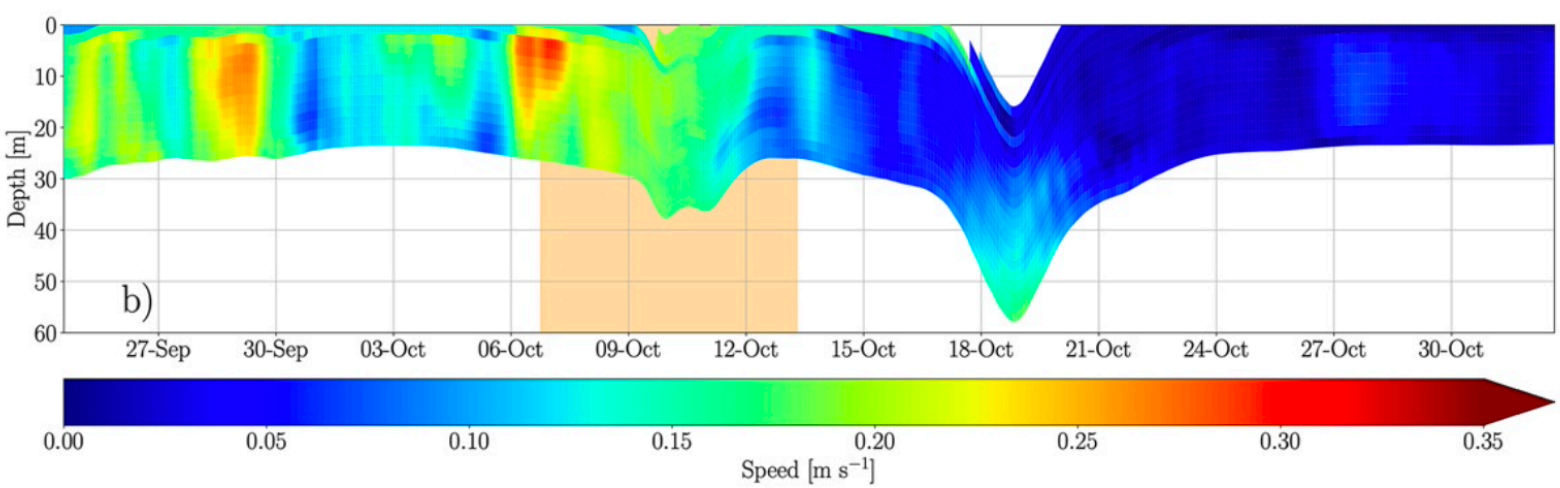
Eddy signature in sea ice motion

- Altough its signature in sea ice is not directly visible, mooring observations suggest the passage of an eddy







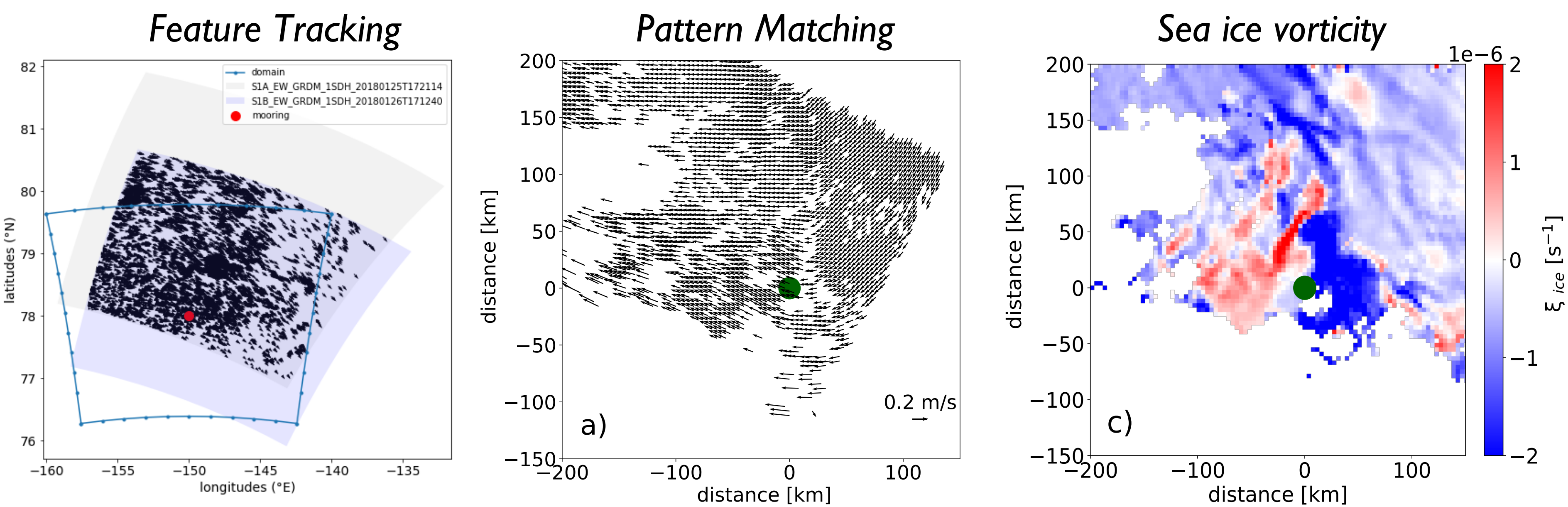


Cassianides, Lique & Korosov 2021

Eddy signature in sea ice motion

- We reconstruct the sea ice drift by using the correlation between successive SAR images la dérive de glace par corrélation d'images SAR successives

- Sea ice vorticity reveals a strong anomaly: the dipole exhibits similar caracteristics to the ocean dipole seen at the mooring (size ~ 80km, persitance ~1 week).
  ice vorticity ~2.10^{-6} / ocean vorticity ~1.5.10^{-5}



Time average: Oct. 7-13 2017

Cassianides, Lique & Korosov 2021

Eddy signature in sea ice motion at the Arctic scale

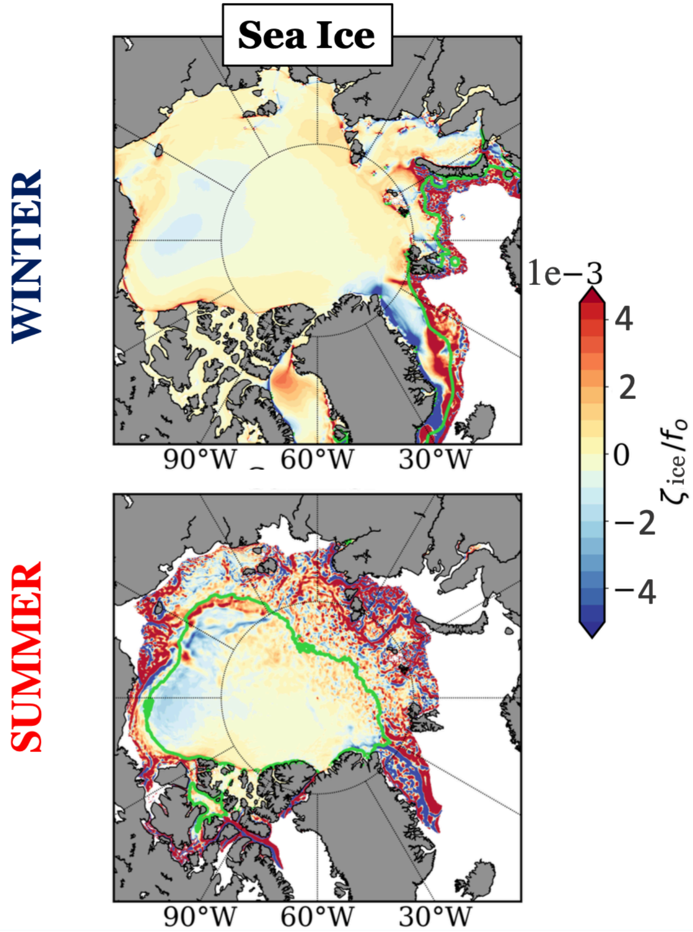
Momentum equation for sea ice

$$m\frac{D\mathbf{u}}{Dt} = -mf\hat{\mathbf{k}} \times \mathbf{u} + \tau_{\text{air}} + \tau_{\text{ocean}} - m\nabla\phi(0) + \mathbf{F}$$

With

$$\begin{aligned}\tau_{\text{air}} &= \rho_{\text{air}} C_{\text{air}} |\mathbf{U}_{\text{air}} - \mathbf{u}| R_{\text{air}} (\mathbf{U}_{\text{air}} - \mathbf{u}) \\ \tau_{\text{ocean}} &= \rho_{\text{ocean}} C_{\text{ocean}} |\mathbf{U}_{\text{ocean}} - \mathbf{u}| R_{\text{ocean}} (\mathbf{U}_{\text{ocean}} - \mathbf{u})\end{aligned}$$

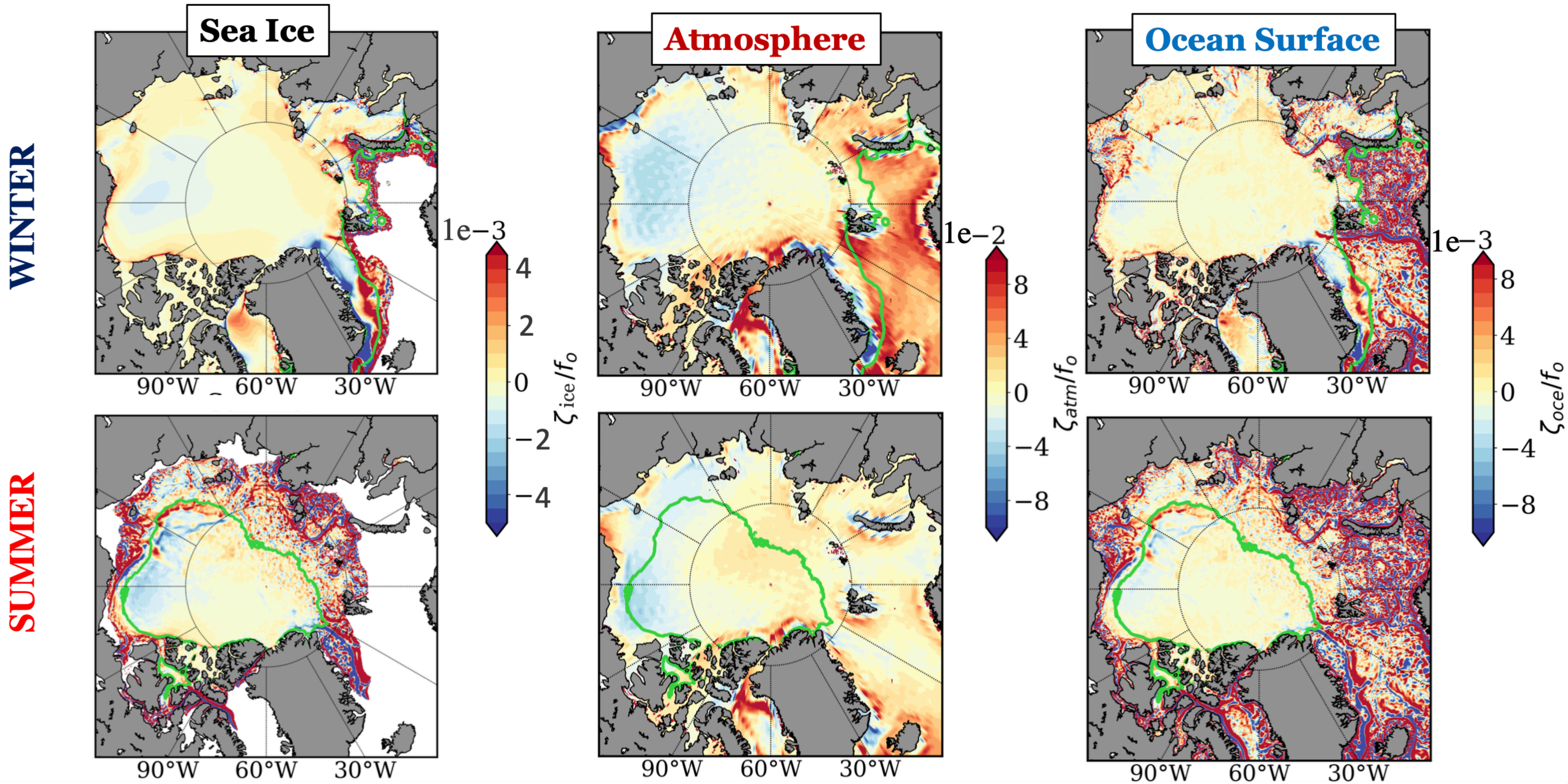
$\mathbf{F} = \nabla \cdot \sigma$ *aka the rheology*



Data from CREG12 simulation (3-4km resolution); PhD thesis of A. Cassianides 2023

Eddy signature in sea ice motion at the Arctic scale

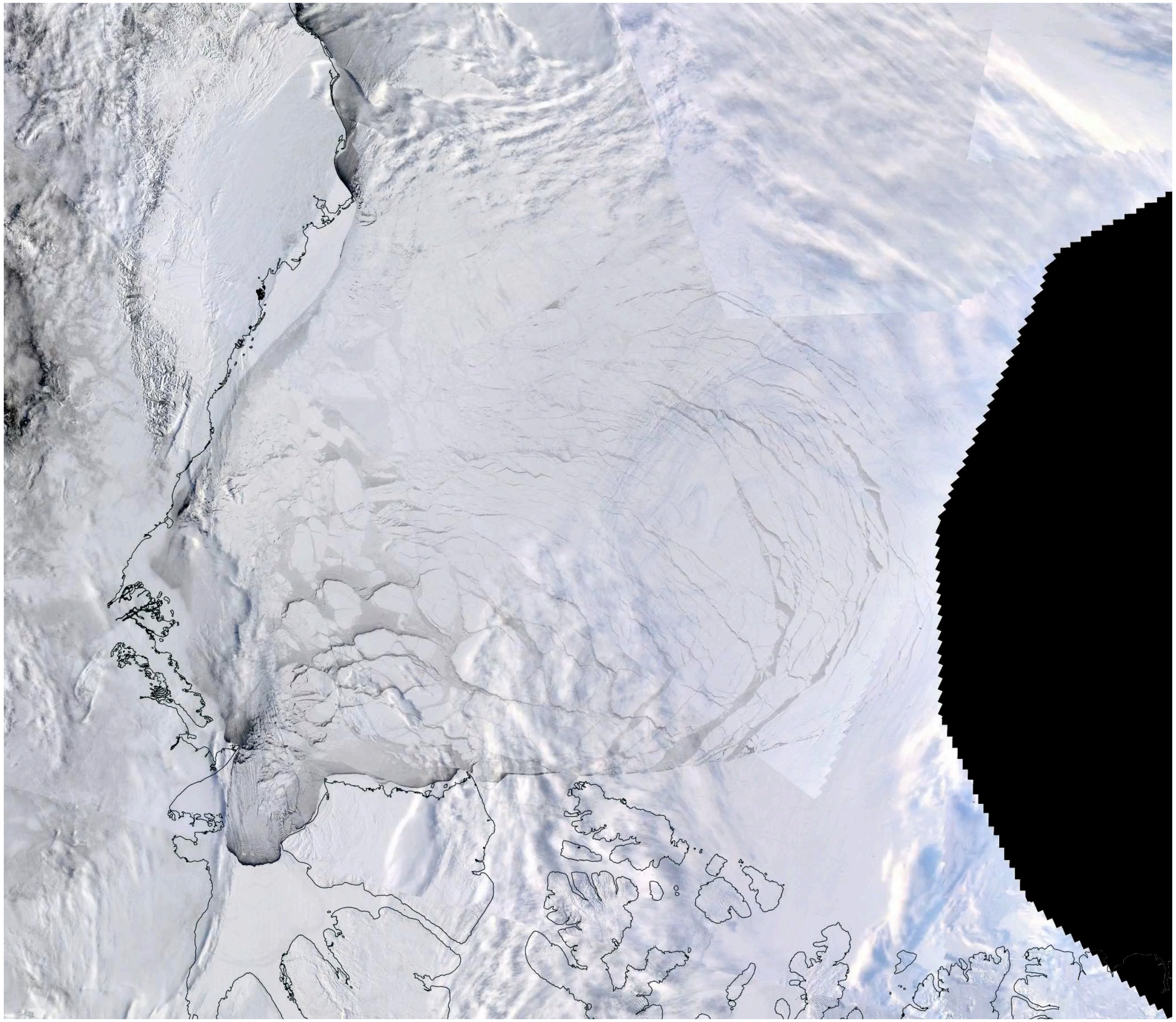
- At the pan-Arctic scale, sea ice vorticity carries the signature of the both atmosphere and the ocean (*specially in summer, when sea ice concentration is below 80% and the rheology gets negligible*)



Data from CREG12 simulation (3-4km resolution); PhD thesis of A. Cassianides 2023

Ocean – sea ice – atmosphere interactions at small scale

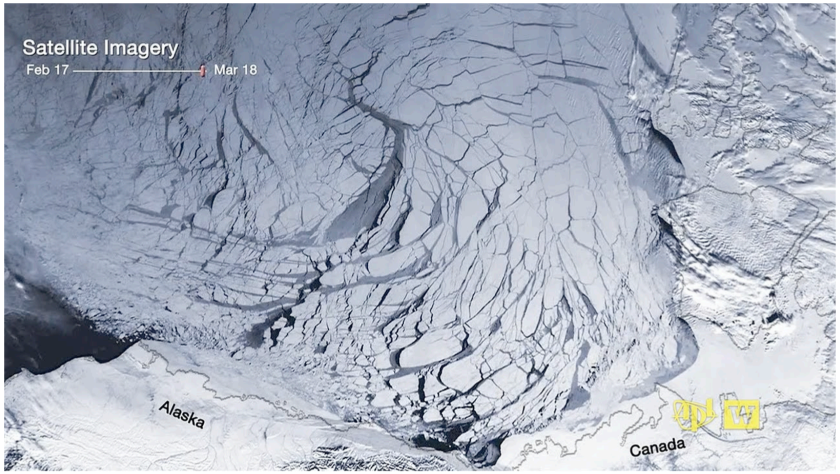
- The case of a storm in the Beaufort Sea in May 2017



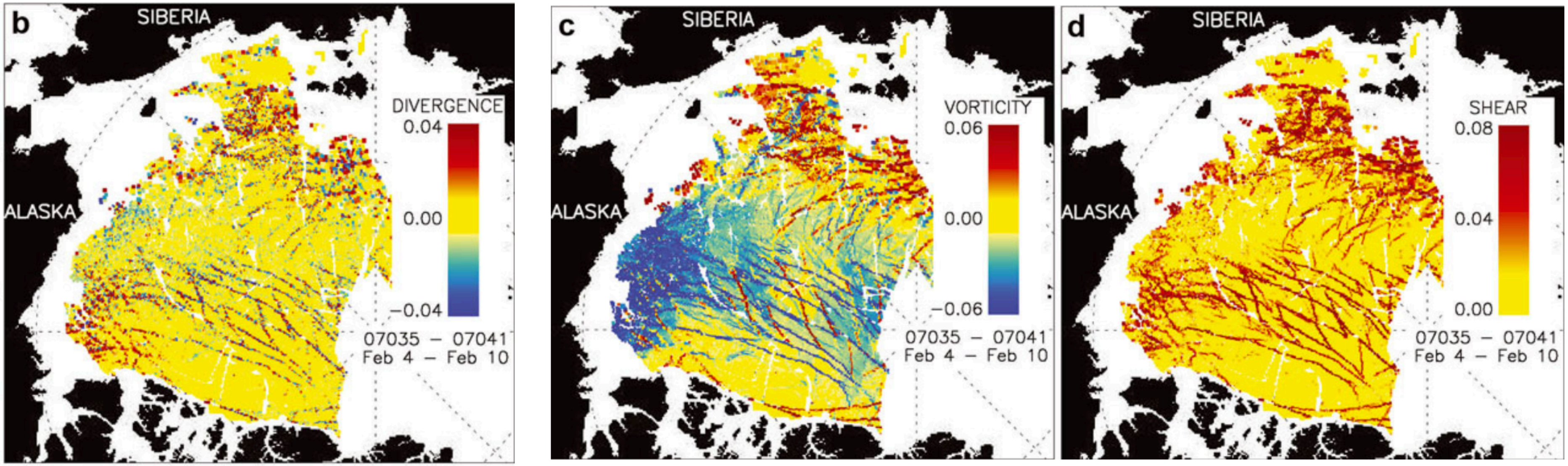
Observations from MODIS

Ocean – sea ice – atmosphere interactions at small scale

- Linear Kinematic Feature (LKF) = *Localized and intensified deformation of the sea ice drift*



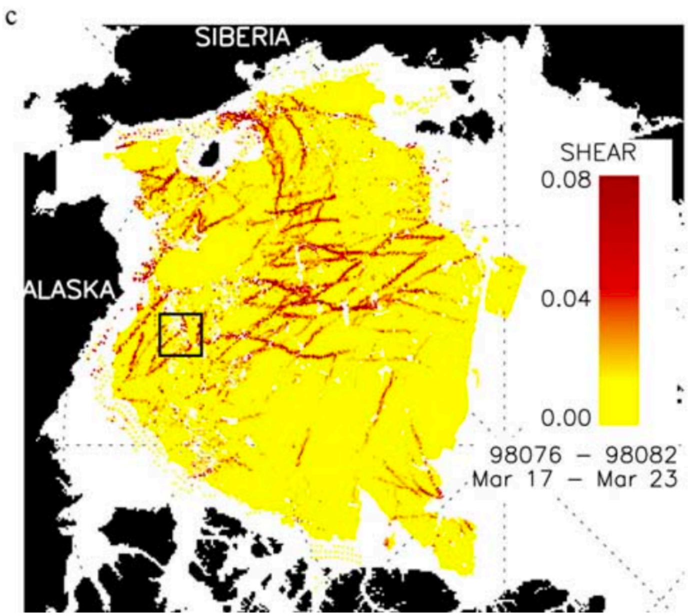
Sea ice deformation from SAR images

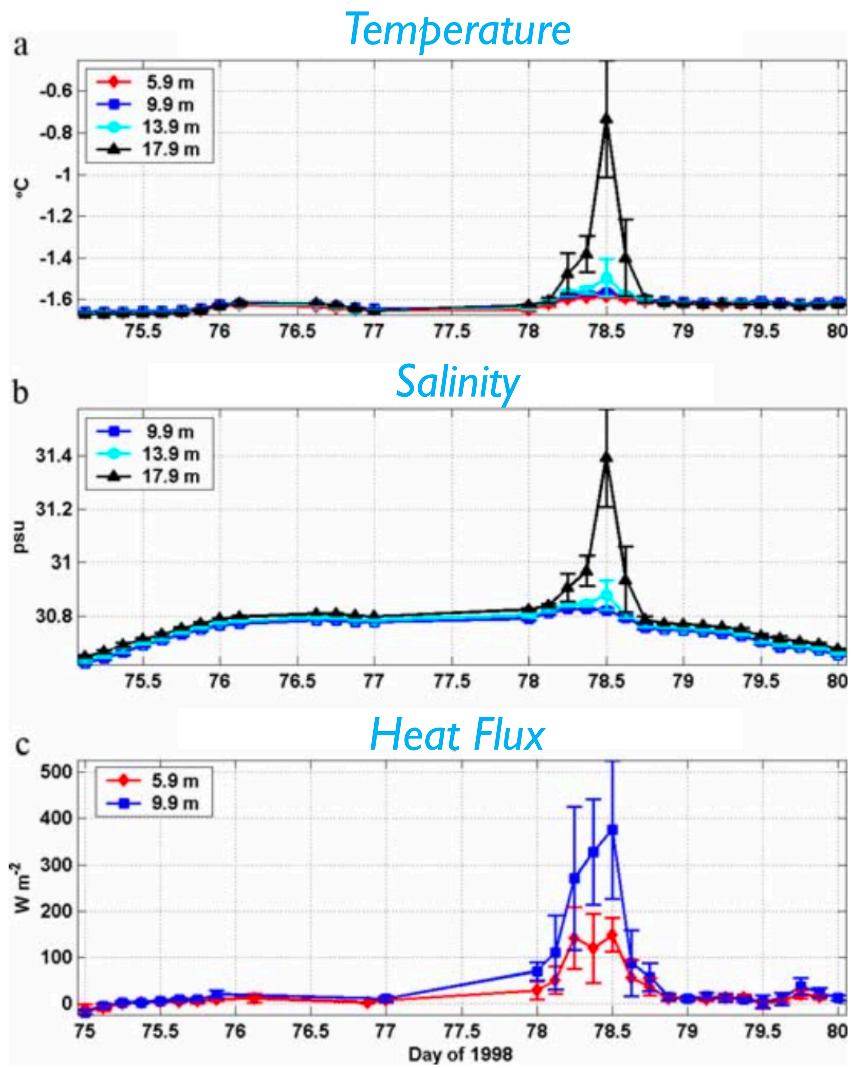


Kwok 2011

Ocean – sea ice – atmosphere interactions at small scale

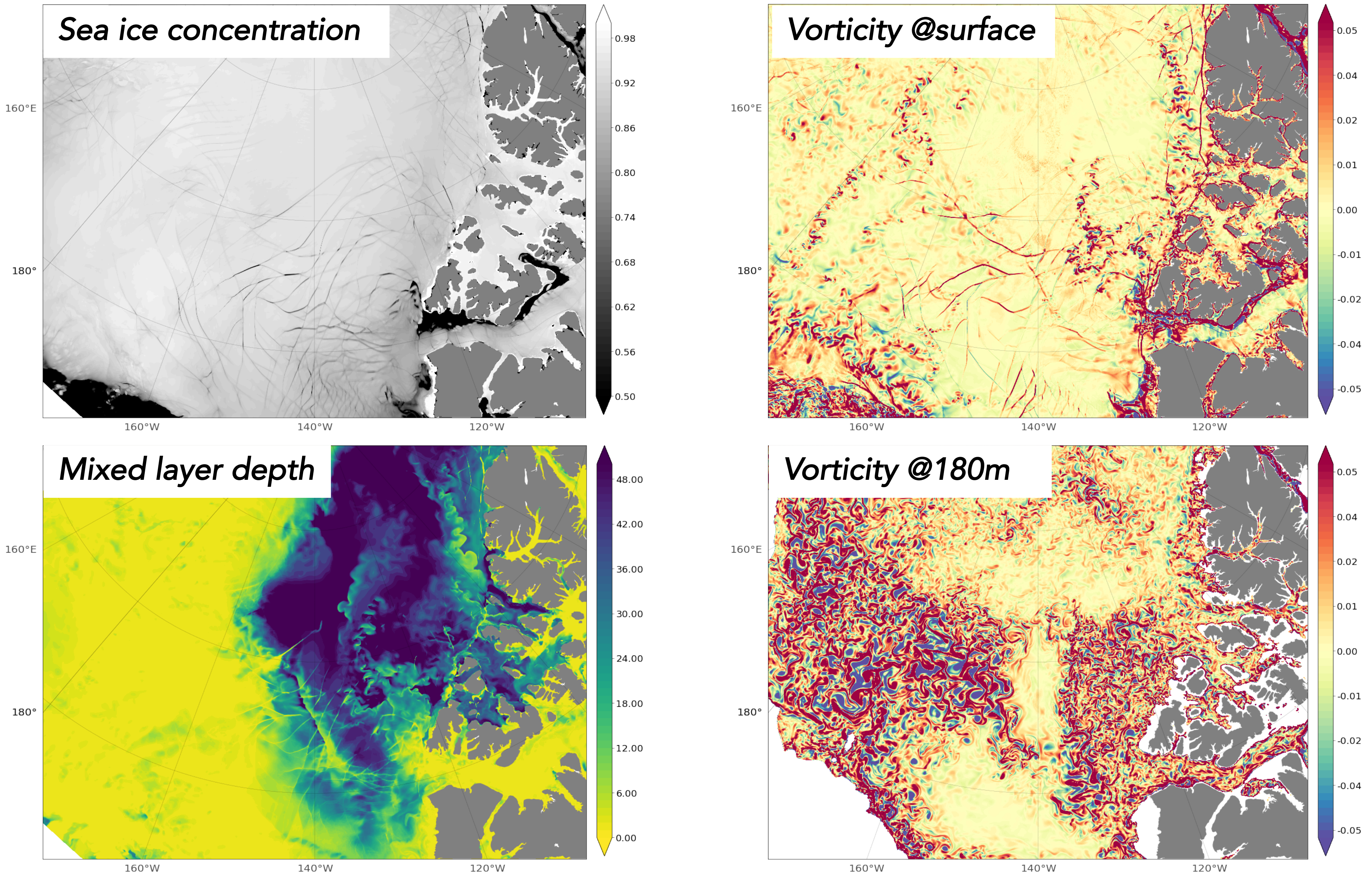
- Large upwelling observed within the lead
- Overall, observations suggest that LKF are priviledged locations for exchanges between the ocean and the atmosphere





McPhee 2005

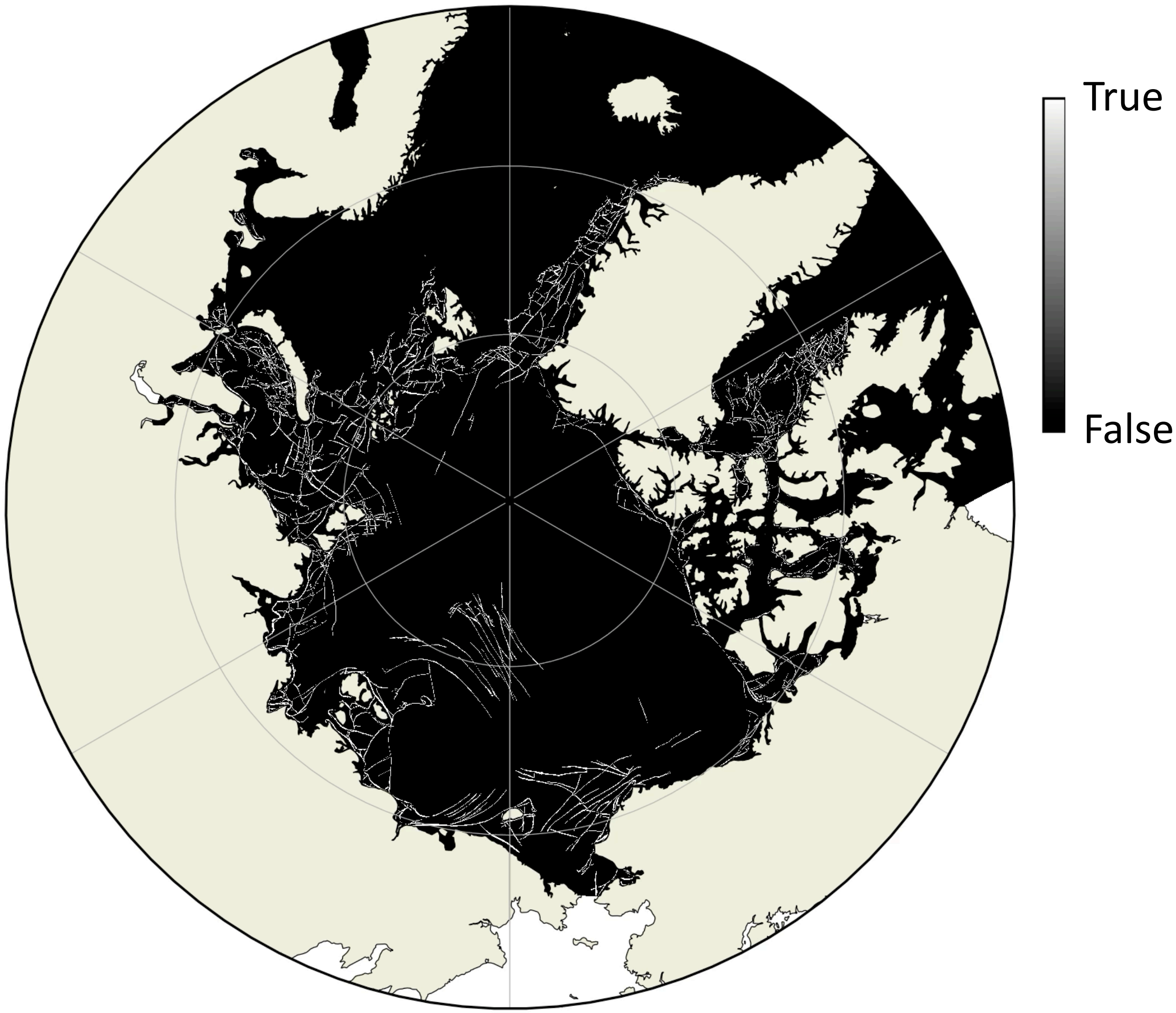
Ocean – sea ice – atmosphere interactions at small scale



Snapshot for June 23rd 2003, data from SEDNA @ 800m resolution

Ocean – sea ice – atmosphere interactions at small scale

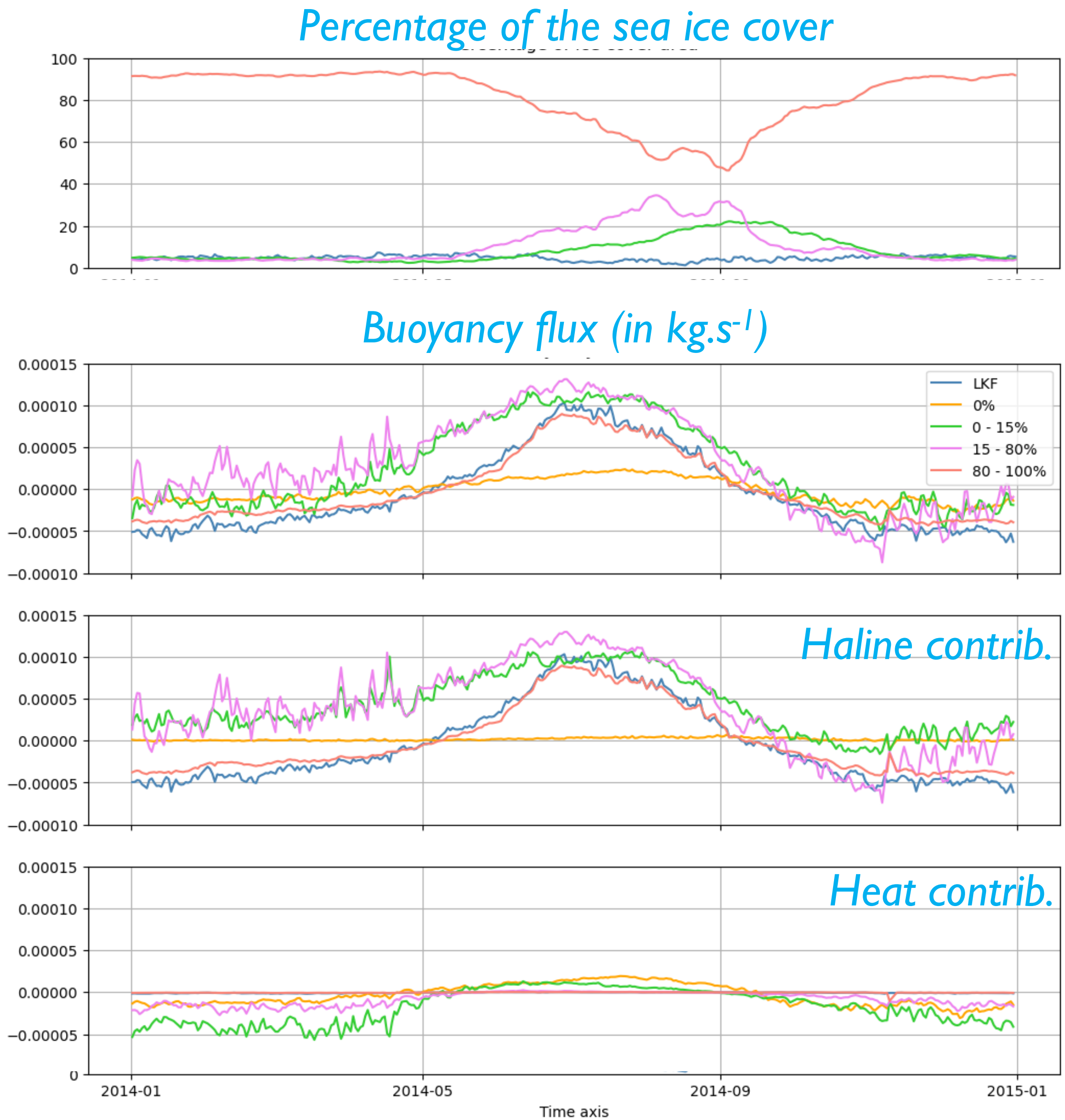
- LKF detection (based on sea ice shear)



data from SEDNA @ 800m resolution; Postdoc of J. Martinez-Moreno

Ocean – sea ice – atmosphere interactions at small scale

- LKF represents around 1% of the surface of the sea ice pack
- Yet the buoyancy forcing through LKF are 100% of the total flux through the pack, and a significant contribution to the total
- The haline contribution is larger than the heat contrib. And is due to the sea ice formation within the LKF

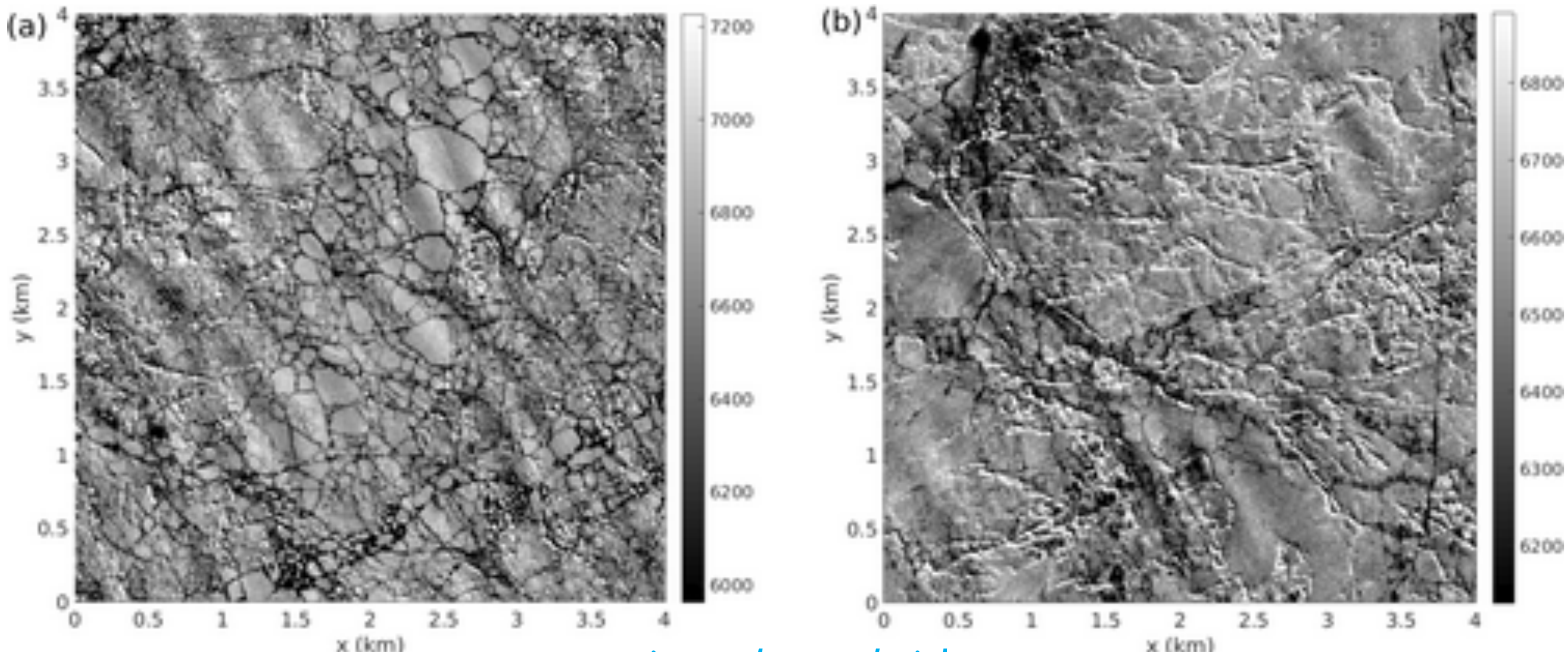


data from SEDNA @ 800m resolution ; Postdoc of J. Martinez-Moreno

Impact of surface waves on sea ice

- Storm over open water also forces surface wave
- SAR images (from the wave acquisition mode) have revealed that the presence of surface wave far into the sea ice pack

SAR images on 23 March 2019



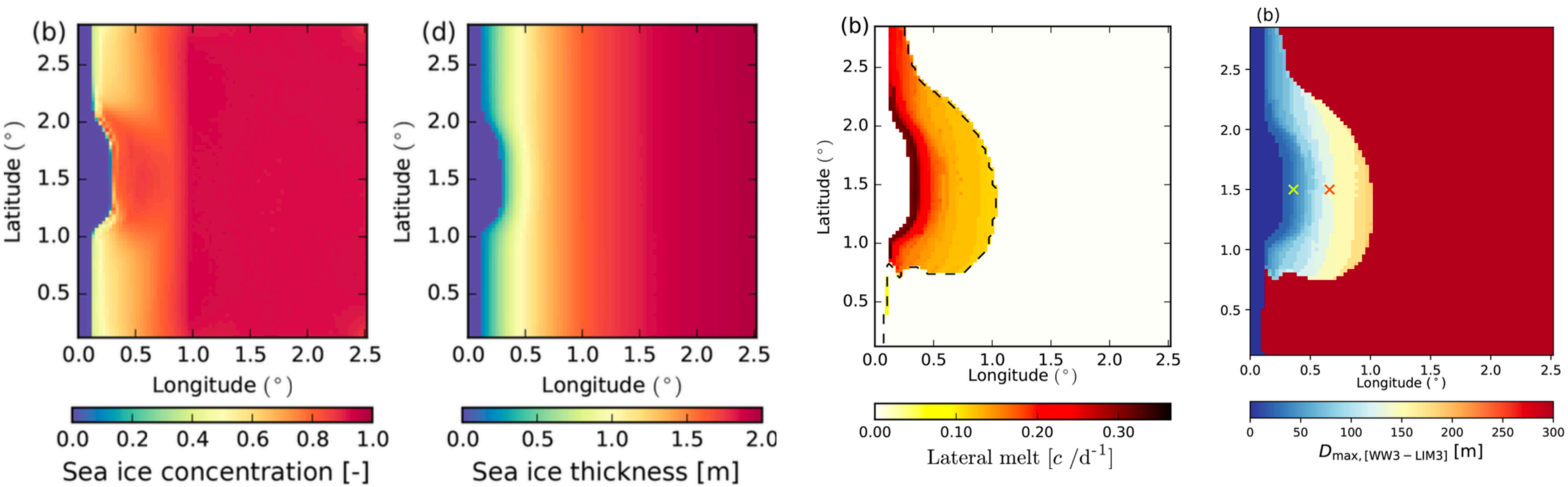
estimated wave height

0.36 m *0.20m*

Collard et al. 2022

Impact of surface waves on sea ice

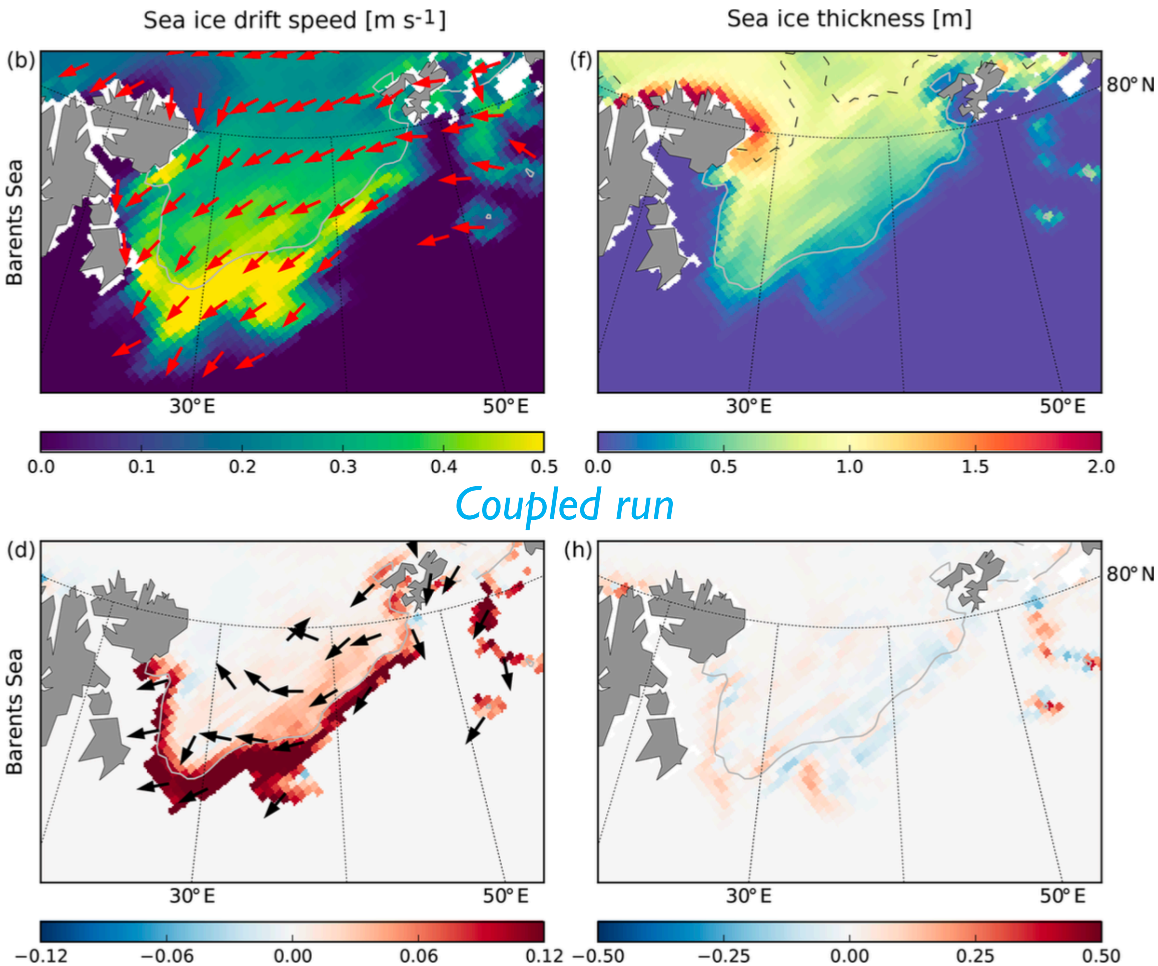
- Starting from a very simplified case, coupling a wave and a sea ice model
- Waves induce a radiative stress, and a modification of the floe size distribution
- After 72h, sea ice gets compacted, broken and melted locally
- In return waves are strongly attenuated!



Boutin, Lique, Ardhuin et al. 2018

Impact of surface waves on sea ice

- The case of a storm in the Barents Sea on 16-17 August 2020:
  southwesterly winds of 15 m/s, significant wave height up to 5m
- 2 simulations performed with CREG4, coupled or not with WavewatchIII



Coupled – Non Coupled

Locally, waves impact sea ice :

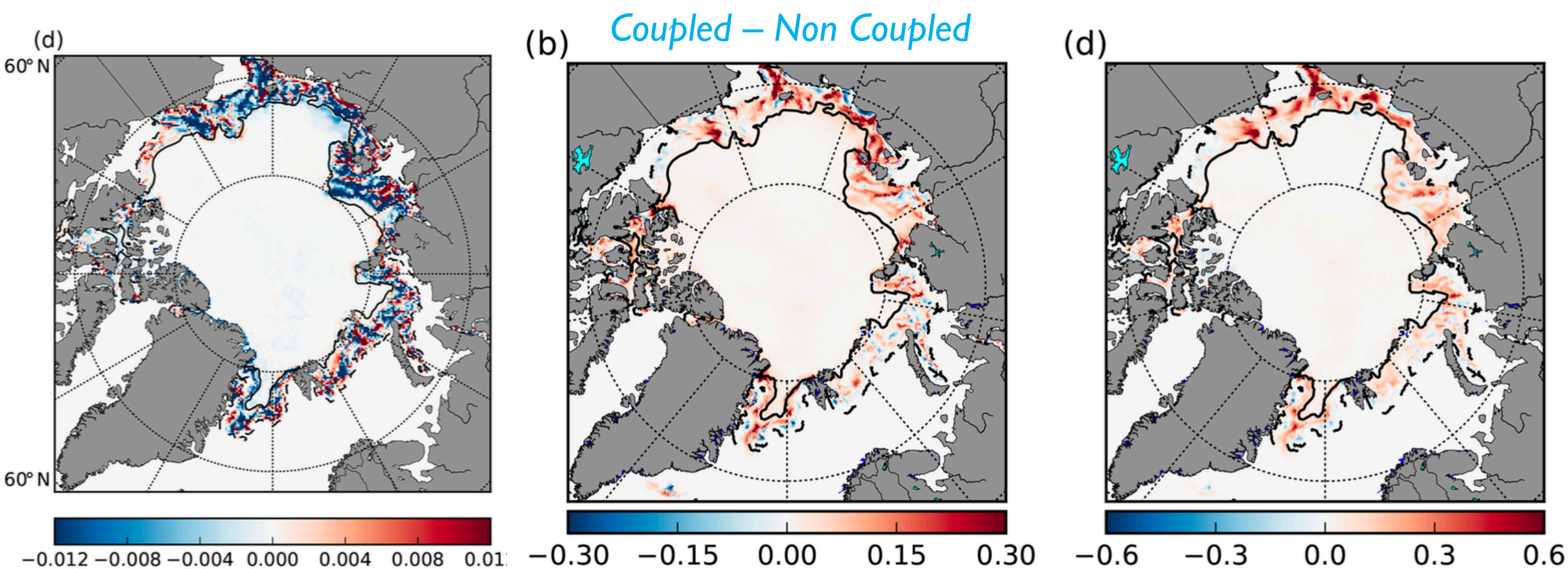
- through a modification of the sea ice drift
- by breaking sea ice, and thus modifying the rate of melt and the thickness

Boutin, Lique, Ardhuin et al. 2018

Impact of surface waves on sea ice

- At the scale of the Arctic Basin, over the one month during the melt season
- The impact of waves remains confined to the marginal ice zone, where it modifies the drift and the melt rate, which in turn can impact the surface ocean temperature and salinity

⚠ We probably underestimate the impact, as the wave and ocean models are not coupled (eg no direct impact on the vertical mixing and the mixed layer!)

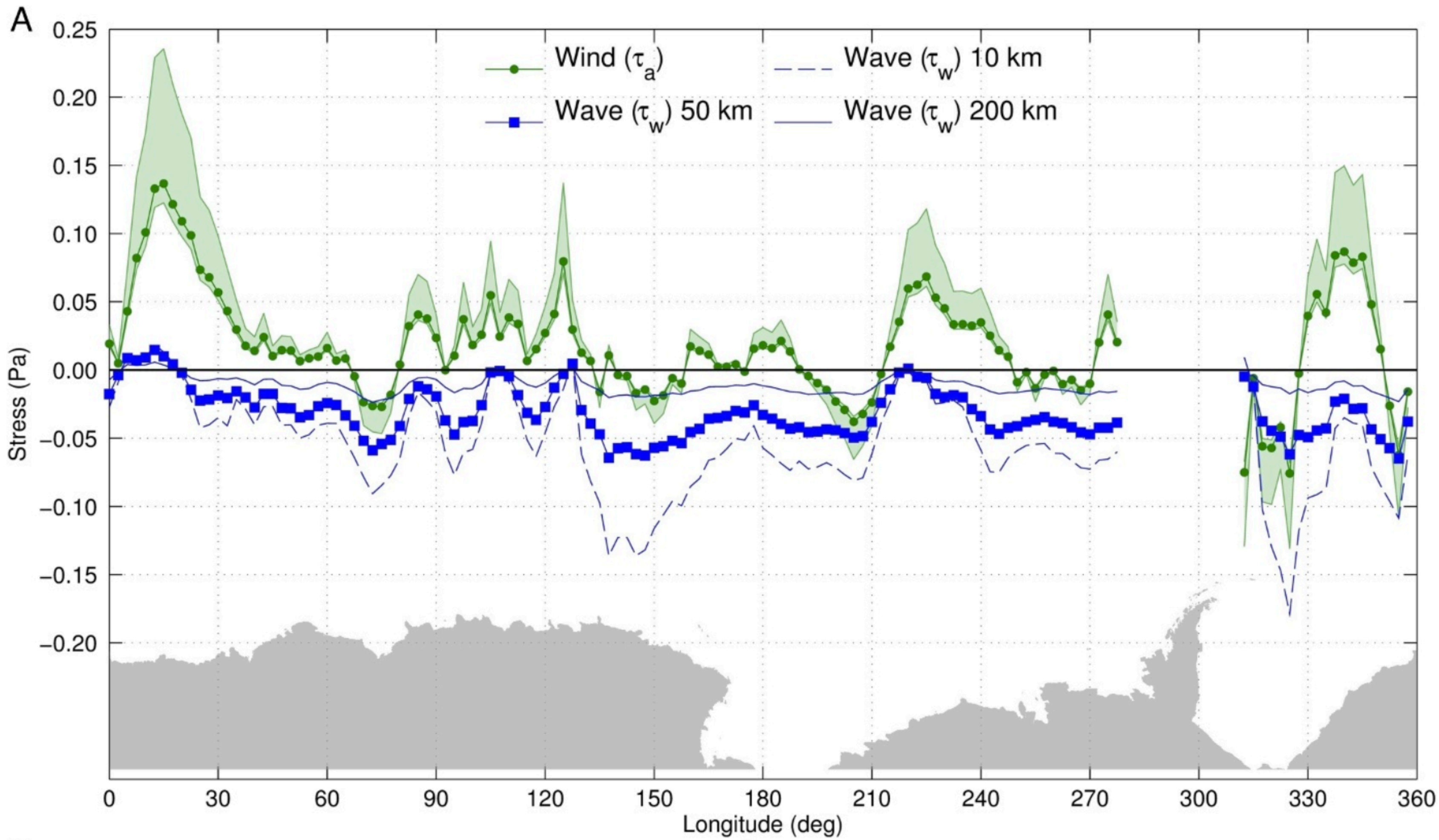


Total volume melt [km^3]   *SST [°C]*   *SSS [psu]*

Boutin, Lique, Ardhuin et al. 2018

Impact of surface waves on sea ice

- In the Southern Ocean, where the ice is thinner, less concentrated, the wave stress is most likely as large as the wind stress, but act in an opposite direction!



Stopa et al. 2018

A tentative conclusion

Some examples of small scale feature important for the ocean-sea ice-atm. interactions (arguably badly/not represented in state-of-the-art models…):

- Ocean eddies can affect the sea ice evolution (formation, drift, melting)
  But the opposite is also true!
  > eddies can arise from instability driven/modulated by sea ice
  > Ability of eddy to survive depends on the sea ice conditions

- Surface fronts can constrain the sea ice evolution
  But the opposite is also true!
  > strong fronts found in the MIZ
  > lot of ocean processes found in the MIZ driven by sea ice (eg deep convection, instabilities…)

- Surface wave modulate the sea ice conditons in the MIZ
  But the opposite is also true!
  > wave attenuation determined by sea ice conditions

- LKF are open window between the ocean and the atmosphere, but their large scale importance remains to be quantified

It is truly a coupled system, that needs to be considered as a whole before we are able to parameterize the impact of the small scale processes.


Merci!
Image of the year (Nature 2018)