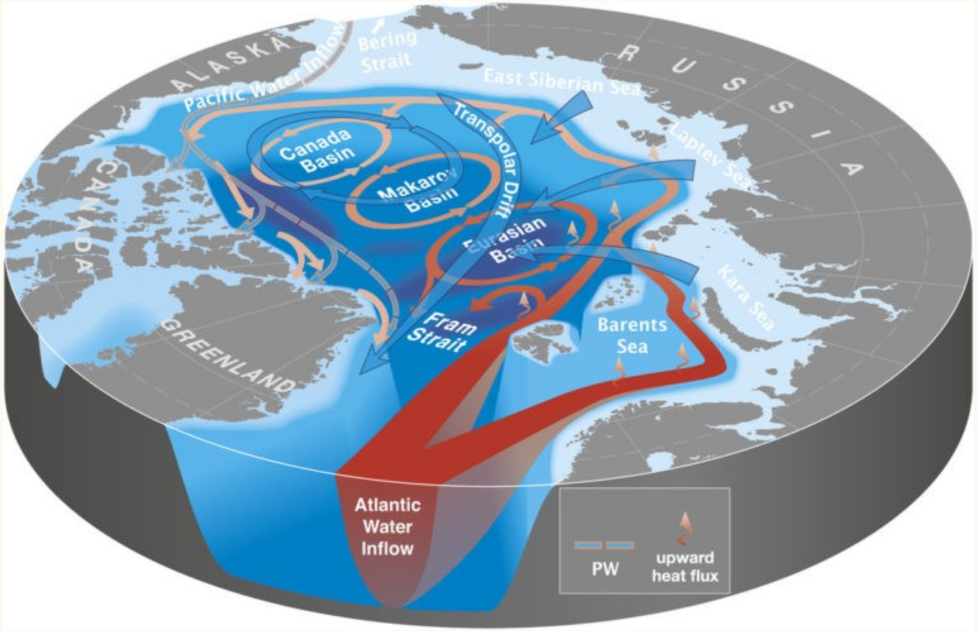
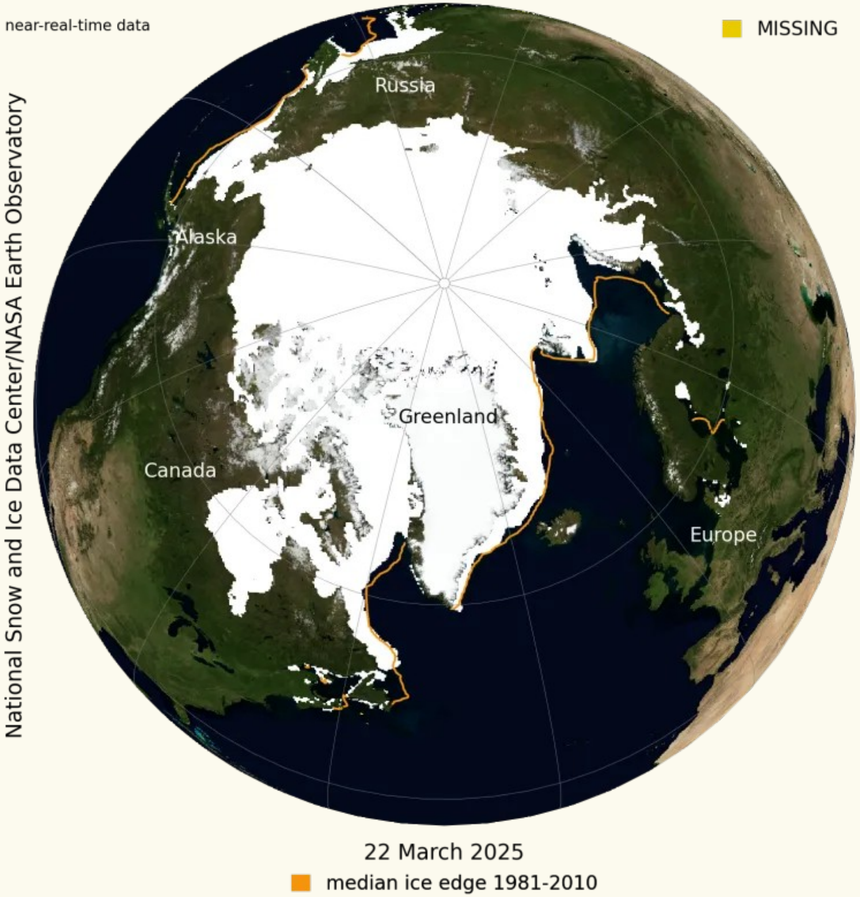
Idealized models for understanding Arctic Ocean Circulation

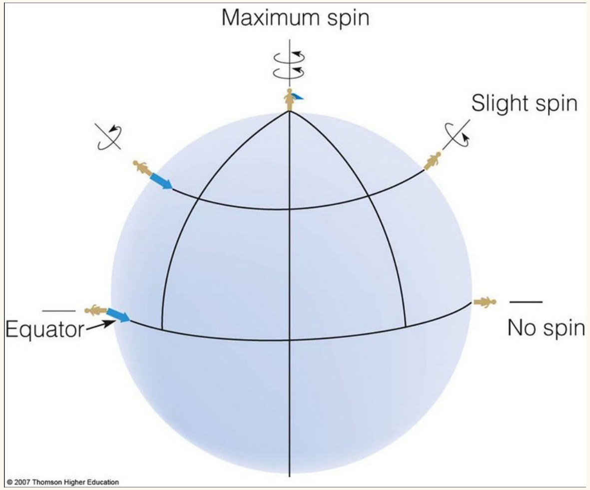
Anna Lina P. Sjur, Pål Erik Isachsen,
Johan Nilsson, Joe LaCasce,
Shaun Johnston, Magnus Dyrmose Ryseth

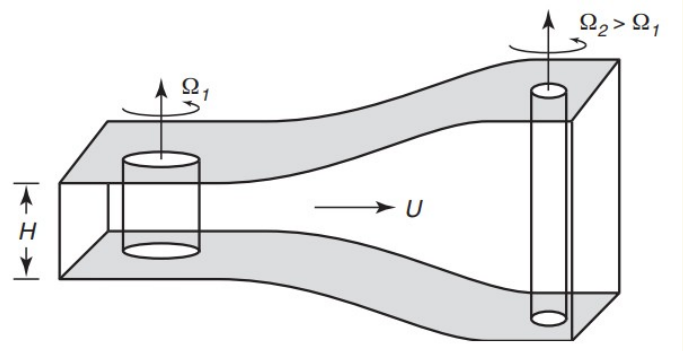


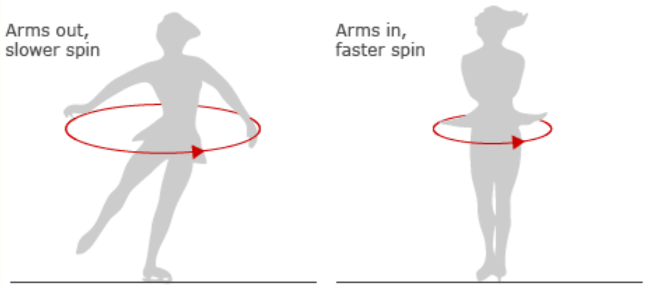


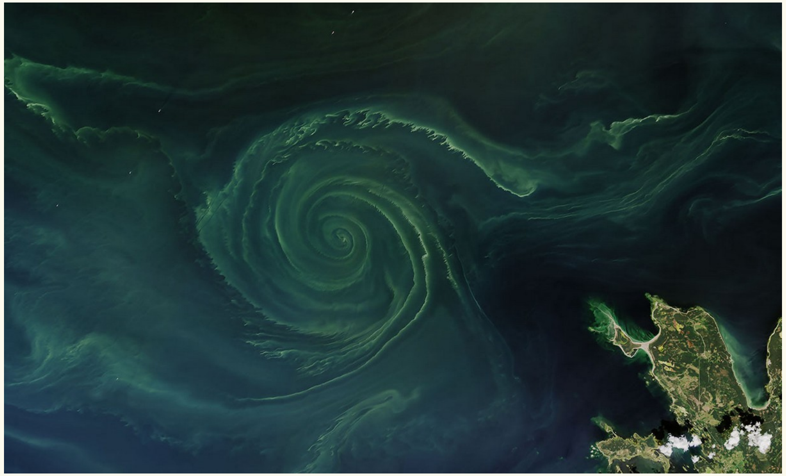
Potential vorticity

$$PV = \frac{\zeta + f}{H}$$





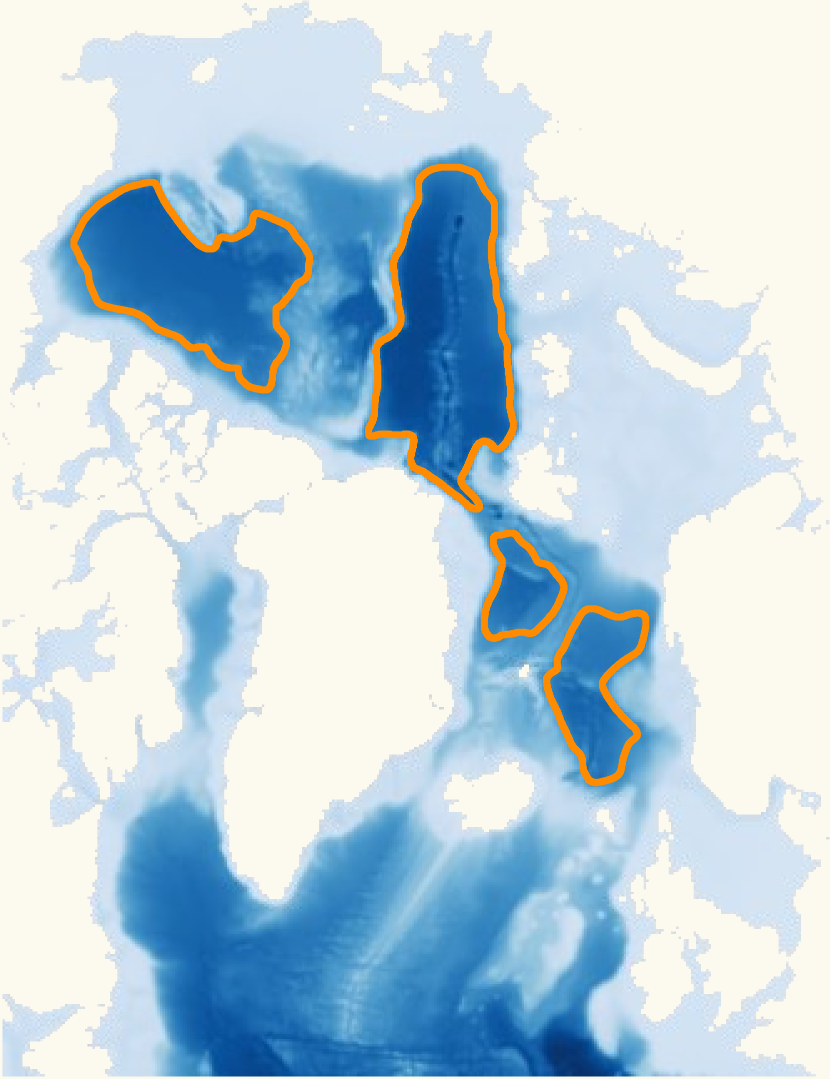




Potential vorticity

- Large scale currents have a strong tendency to follow contours of constant **ambient potential vorticity**.

  These are the “**railway tracks**” of the ocean.

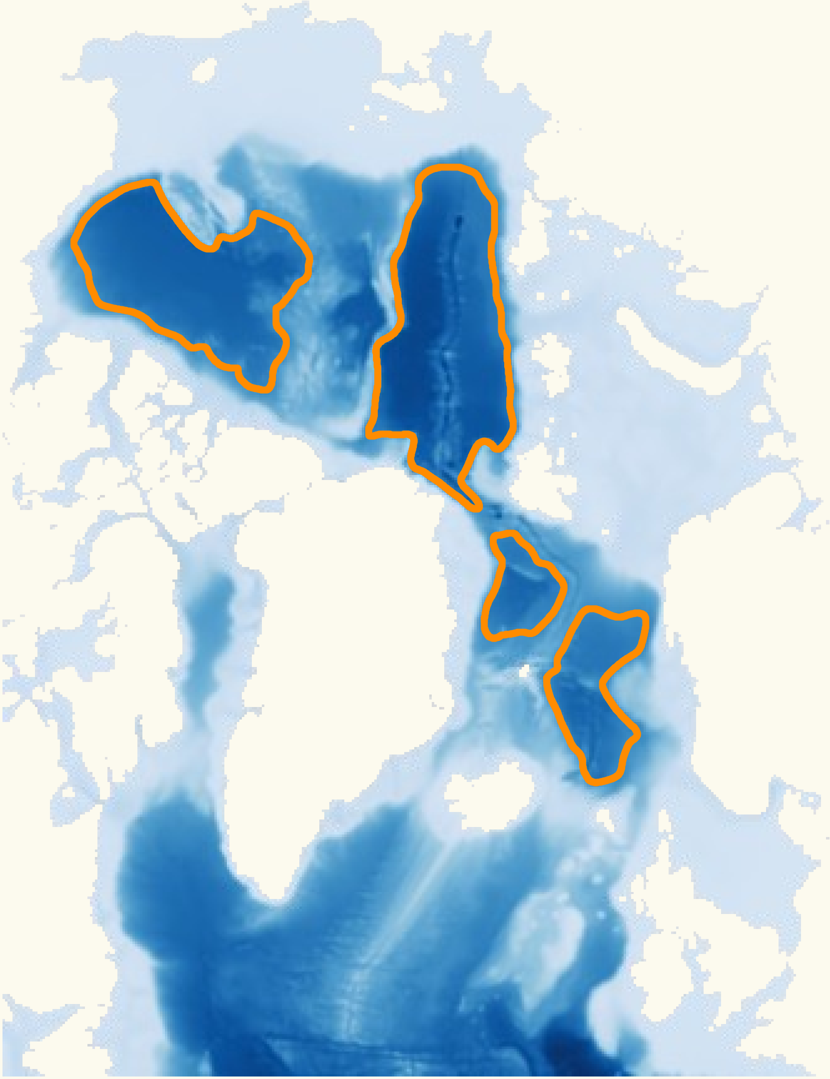


Potential vorticity

- Large scale currents have a strong tendency to follow contours of constant **ambient potential vorticity**.

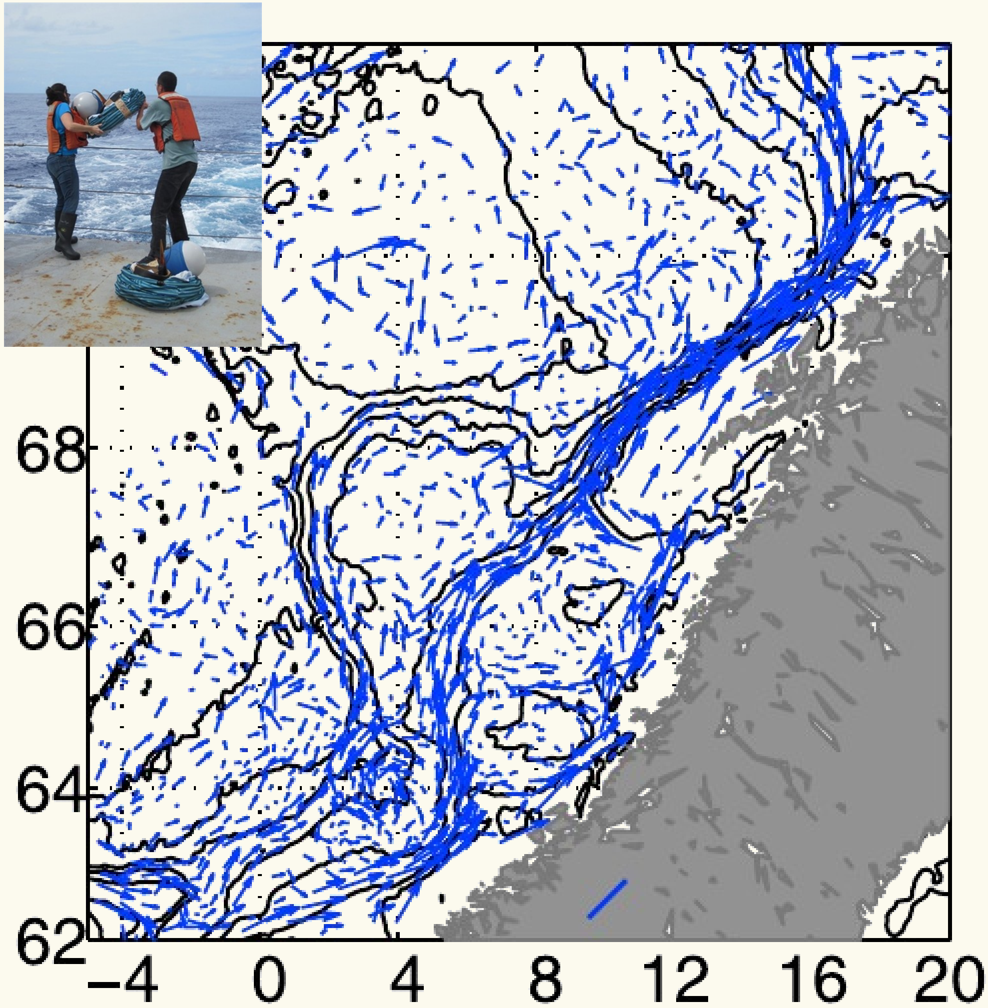
  These are the "**railway tracks**" of the ocean.

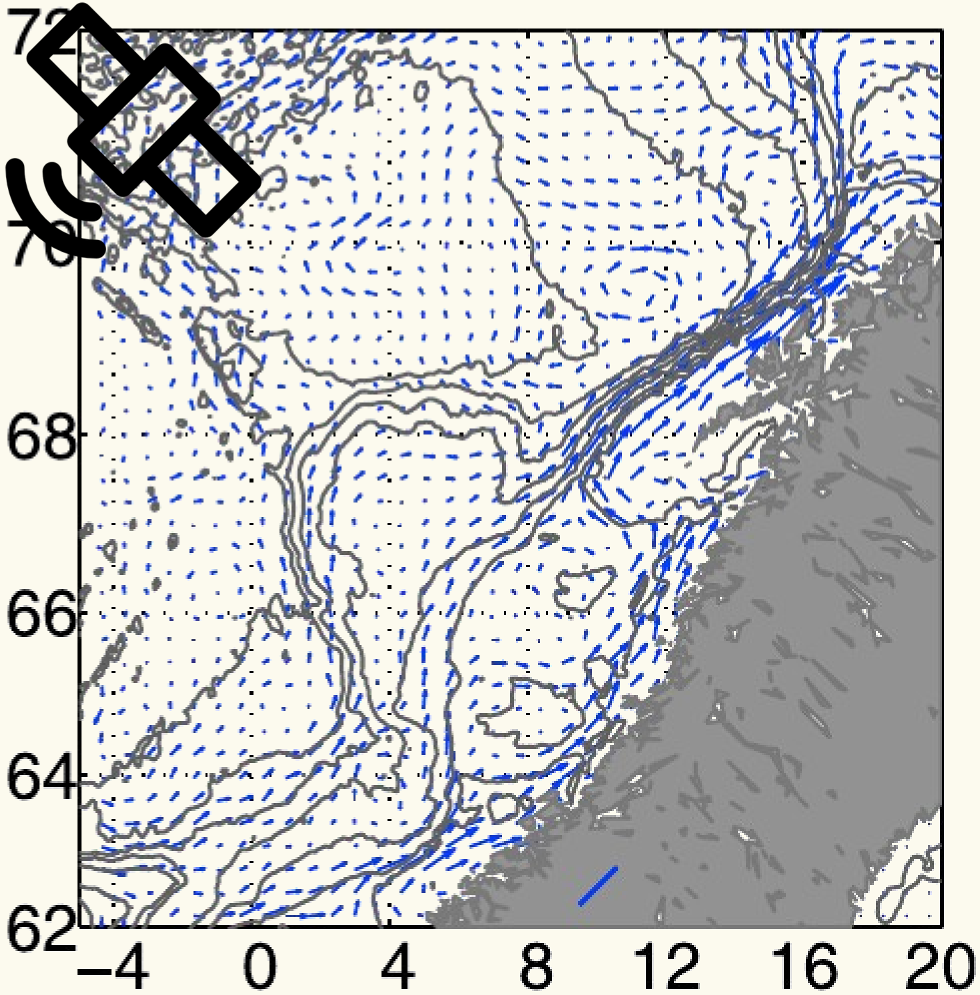
- Potential vorticity dominated by layer thickness at high latitudes → **flow around closed depth contours**.



Observations from the Nordic Seas

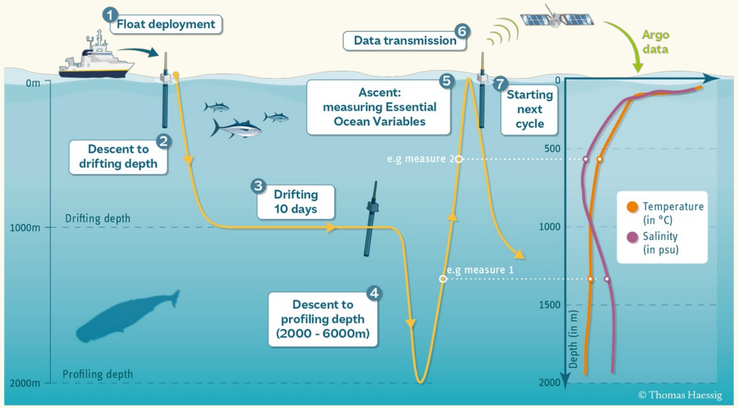
Isachsen et al. (2012)

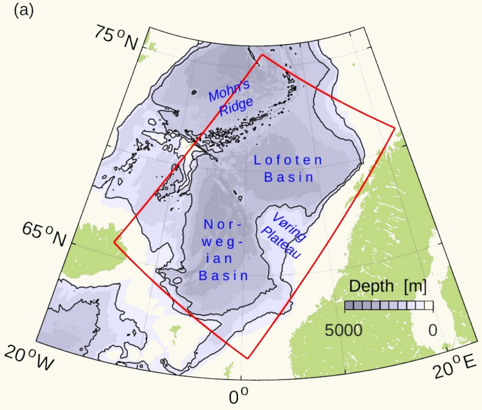


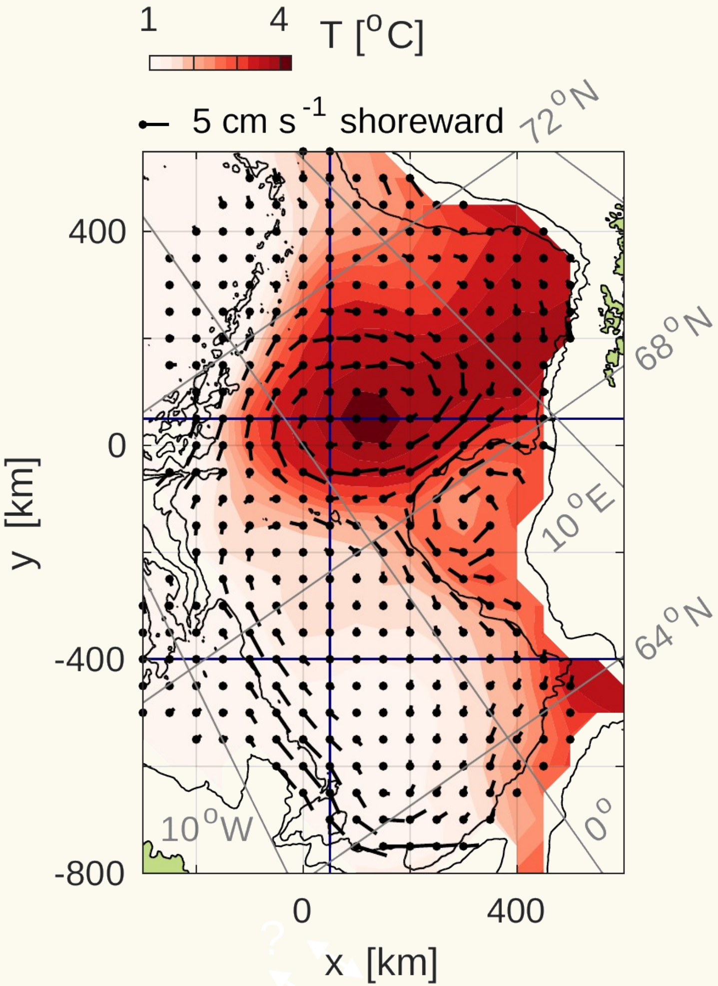


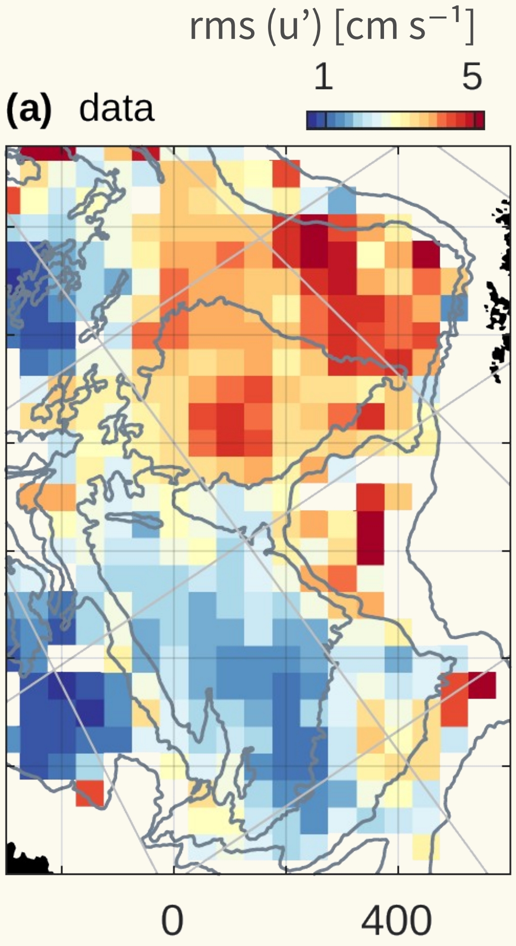
Observations from the Nordic Seas

Johnston et al.
(accepted)

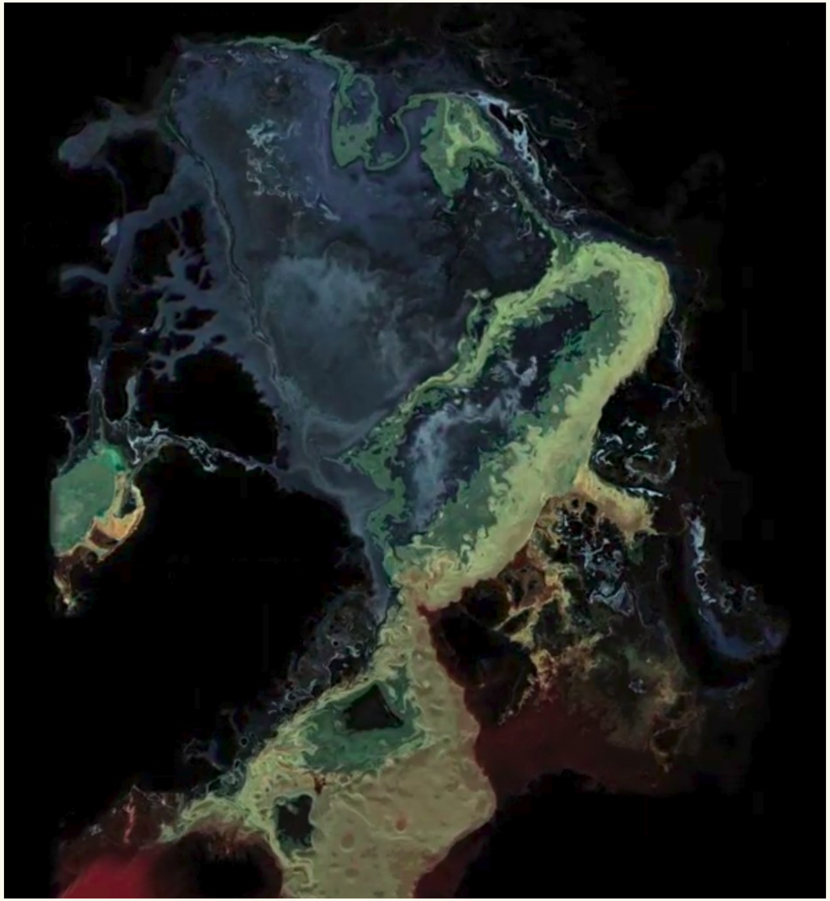




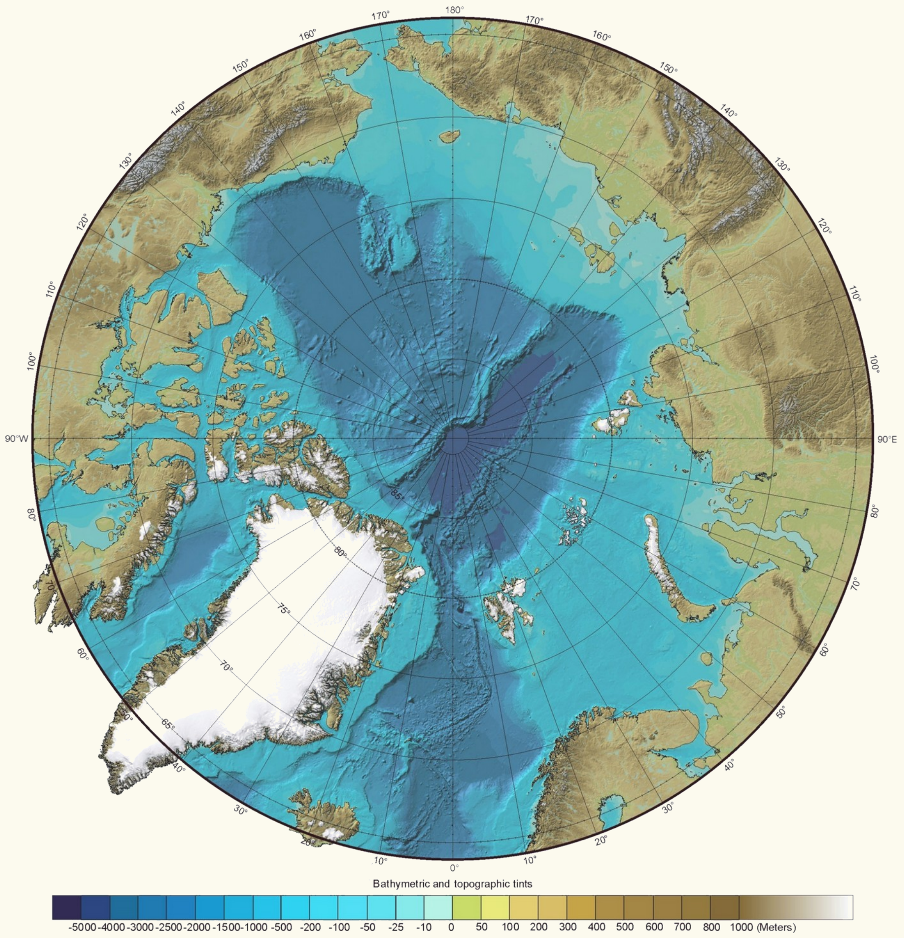


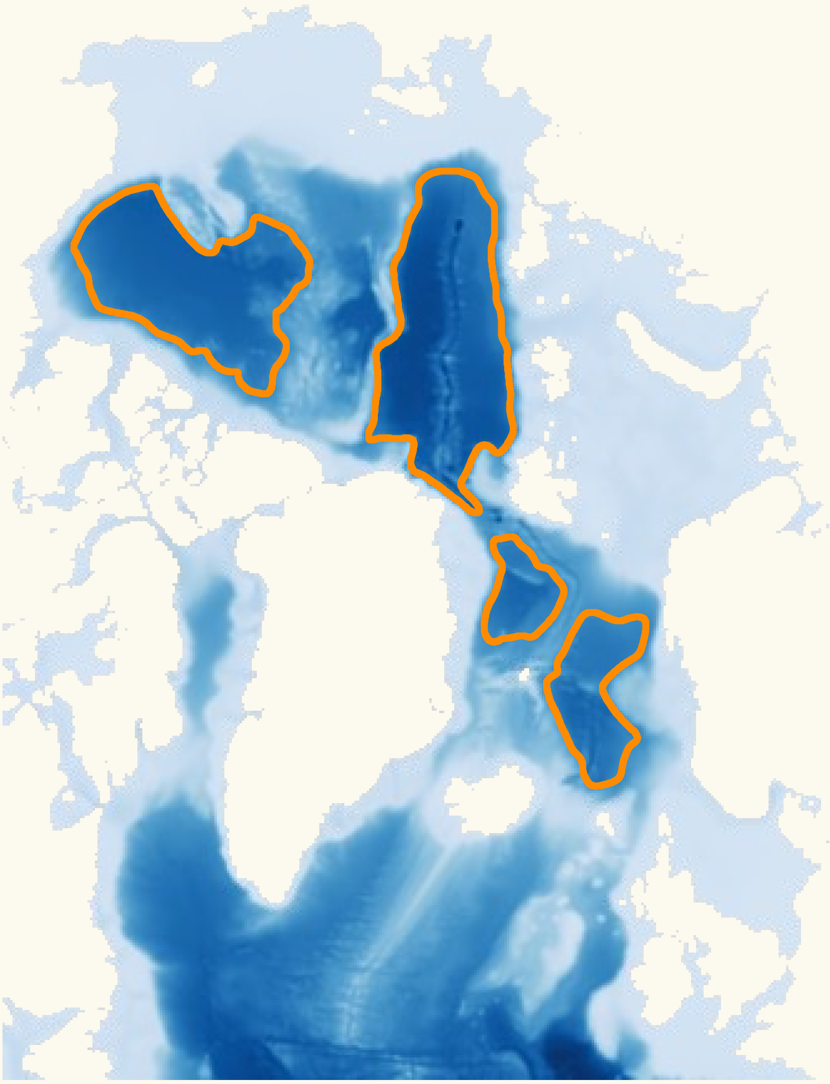


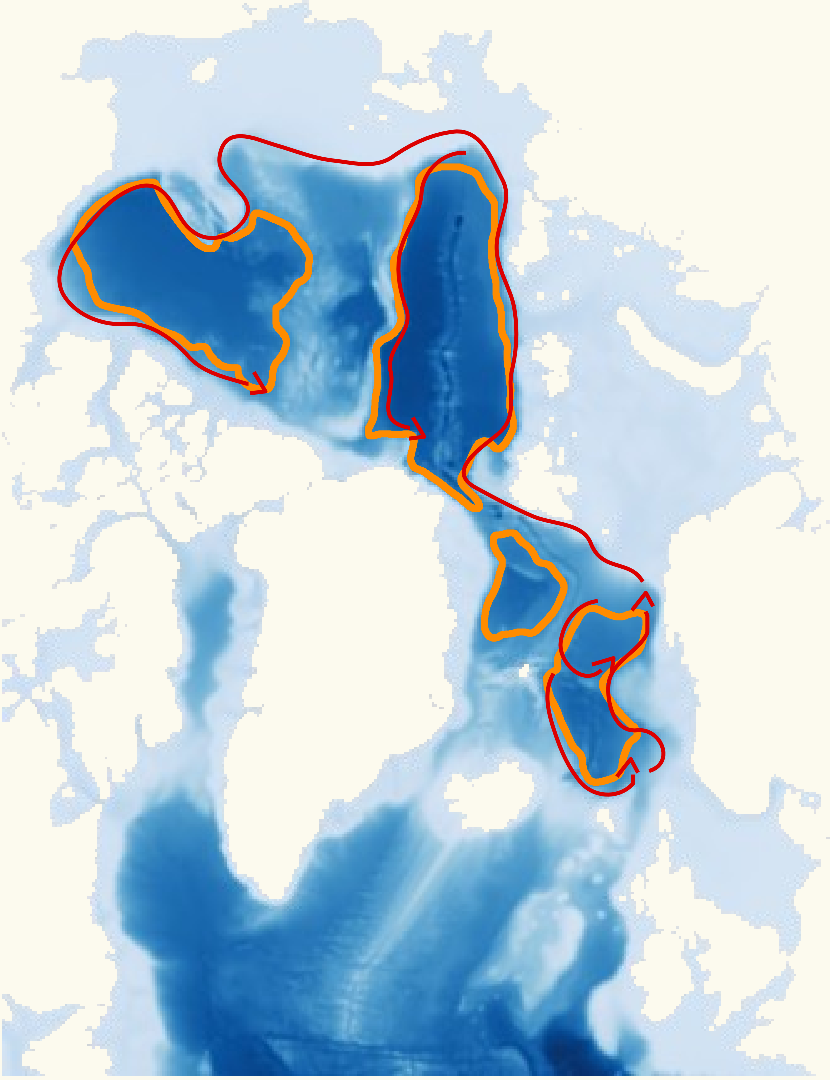
What about in the high Arctic? Rely on modeling



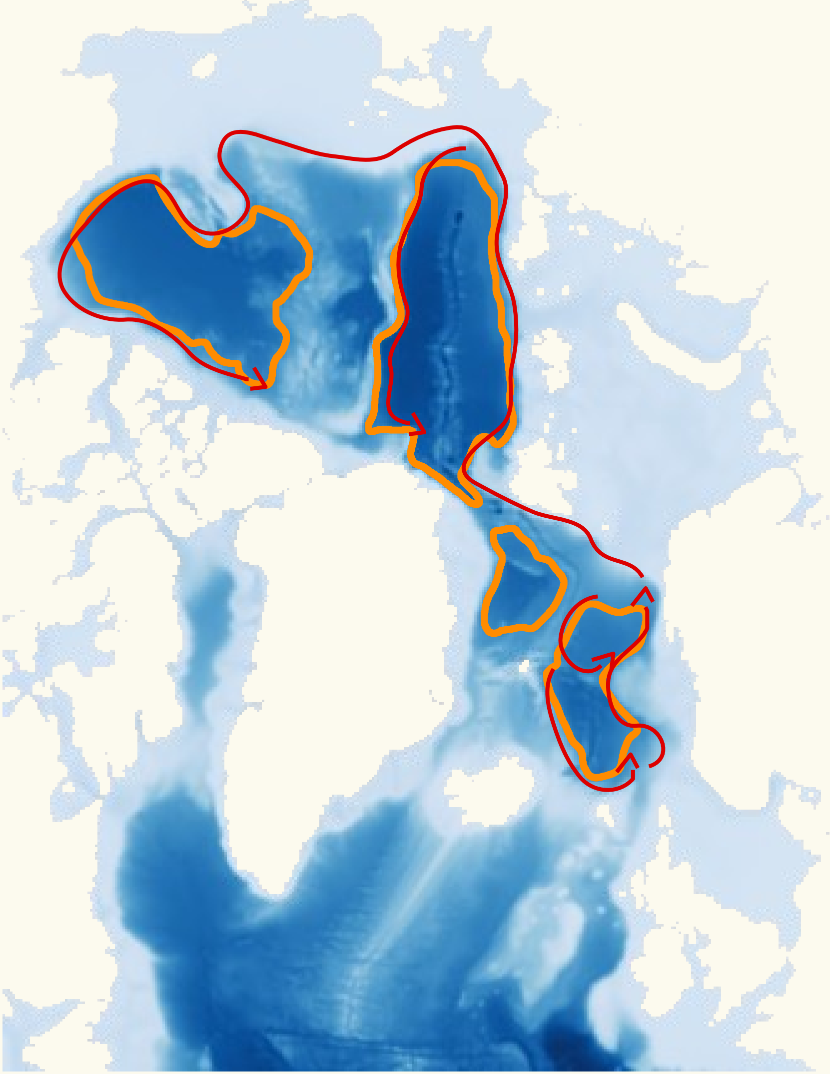
MITgcm, ~3.5 km resolution, TACC





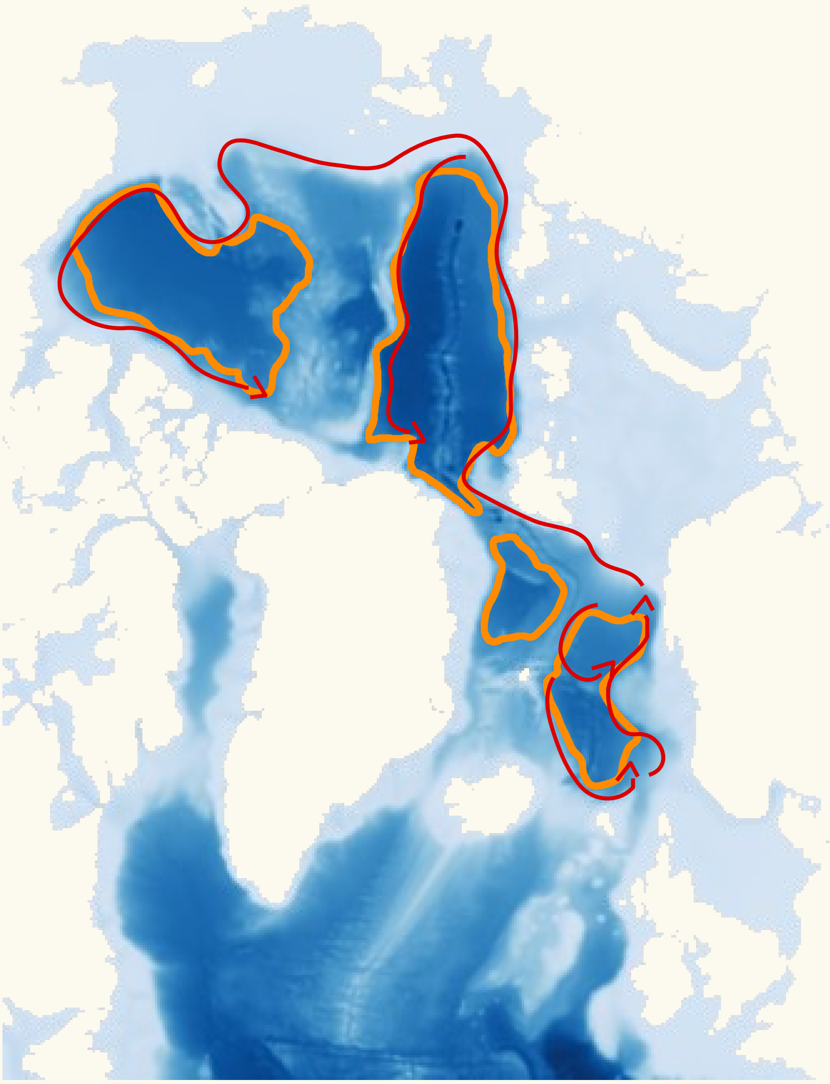


Can we describe Arctic Ocean circulation using linear dynamics?



Can we describe Arctic Ocean circulation using linear dynamics?

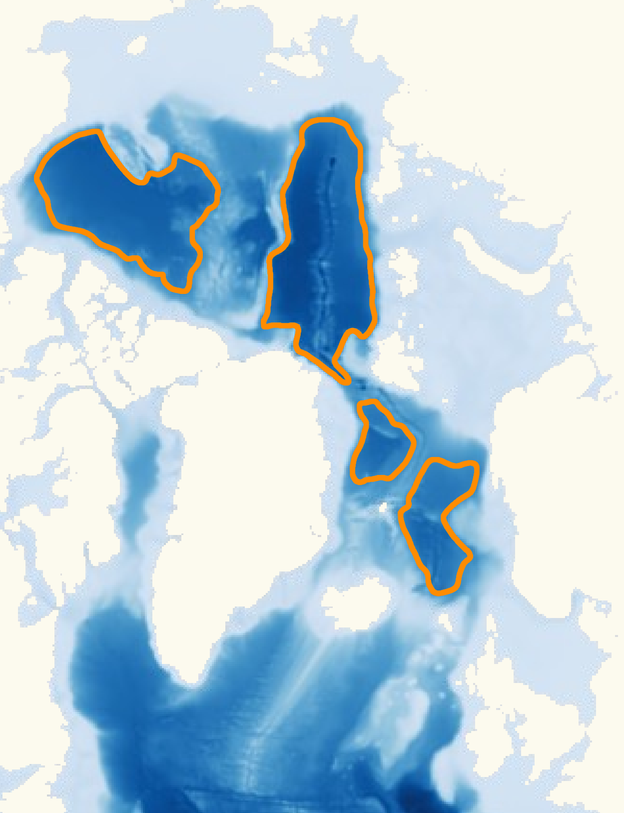
What can linear estimates teach us about the role of non-linearities?



Can we describe Arctic Ocean circulation using linear dynamics?

Link to article

Arctic4
CICE+ROMS
~4 km resolution



Linear model:

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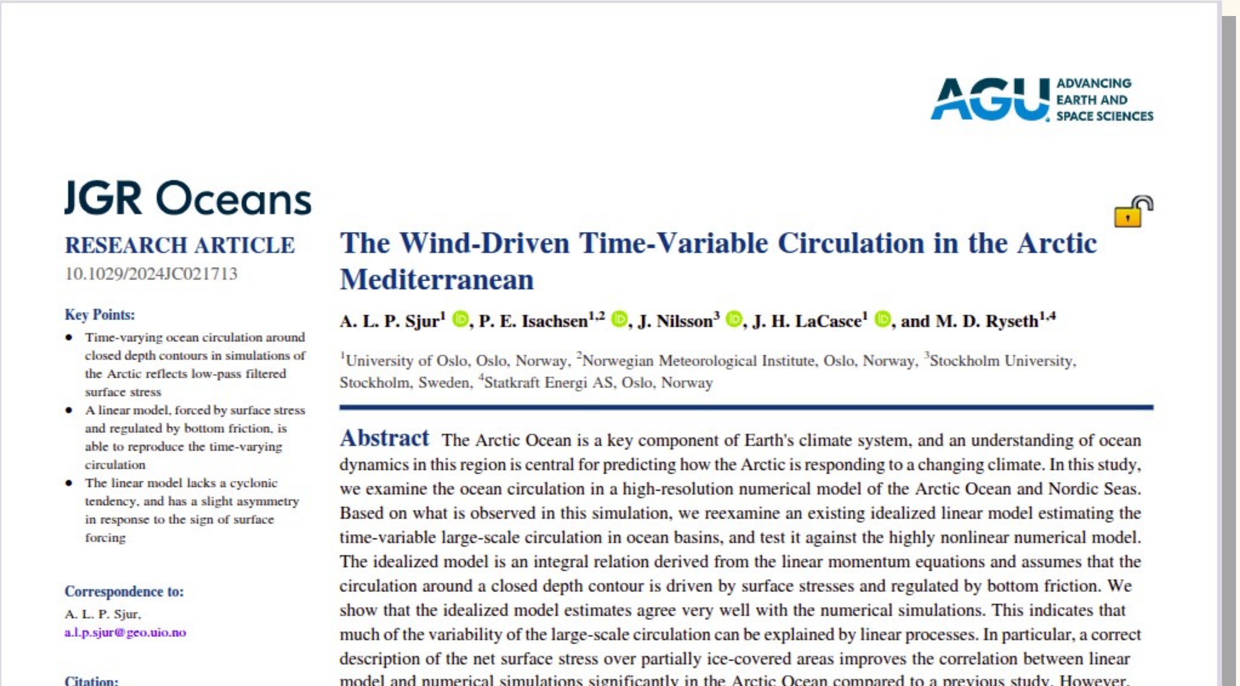
Change in circulation | Surface stress | Bottom drag



ADVANCING EARTH AND SPACE SCIENCES

JGR Oceans

RESEARCH ARTICLE
10.1029/2024JC021713

The Wind-Driven Time-Variable Circulation in the Arctic Mediterranean

A. L. P. Sjur[1], P. E. Isachsen[1,2], J. Nilsson[3], J. H. LaCasce[1], and M. D. Ryseth[1,4]

[1]University of Oslo, Oslo, Norway, [2]Norwegian Meteorological Institute, Oslo, Norway, [3]Stockholm University, Stockholm, Sweden, [4]Statkraft Energi AS, Oslo, Norway

Key Points:

- Time-varying ocean circulation around closed depth contours in simulations of the Arctic reflects low-pass filtered surface stress
- A linear model, forced by surface stress and regulated by bottom friction, is able to reproduce the time-varying circulation
- The linear model lacks a cyclonic tendency, and has a slight asymmetry in response to the sign of surface forcing

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Citation:

Abstract The Arctic Ocean is a key component of Earth's climate system, and an understanding of ocean dynamics in this region is central for predicting how the Arctic is responding to a changing climate. In this study, we examine the ocean circulation in a high-resolution numerical model of the Arctic Ocean and Nordic Seas. Based on what is observed in this simulation, we reexamine an existing idealized linear model estimating the time-variable large-scale circulation in ocean basins, and test it against the highly nonlinear numerical model. The idealized model is an integral relation derived from the linear momentum equations and assumes that the circulation around a closed depth contour is driven by surface stresses and regulated by bottom friction. We show that the idealized model estimates agree very well with the numerical simulations. This indicates that much of the variability of the large-scale circulation can be explained by linear processes. In particular, a correct description of the net surface stress over partially ice-covered areas improves the correlation between linear model and numerical simulations significantly in the Arctic Ocean compared to a previous study. However,

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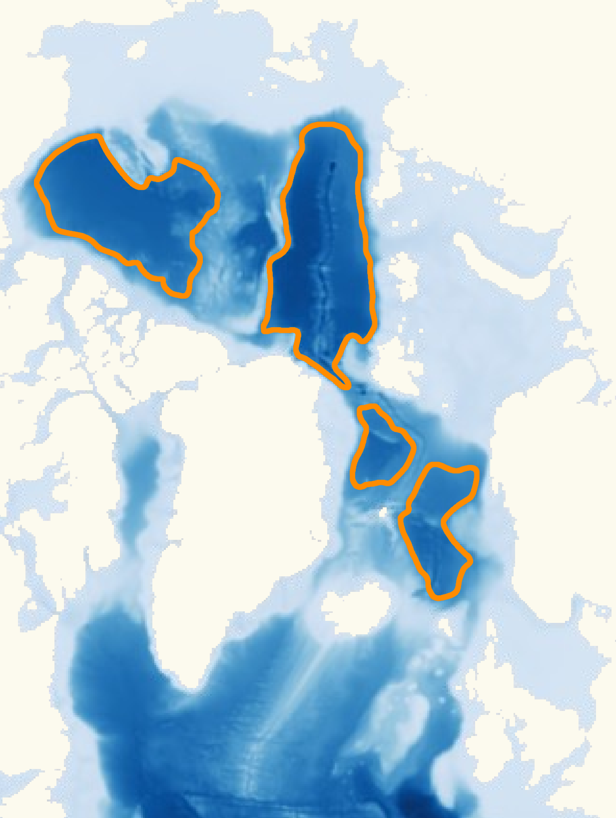

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Change in circulation | Surface stress | Bottom drag

$$\oint \boldsymbol{u}\cdot d\boldsymbol{l} = \exp\left(-\frac{R}{H}t\right)\oint \boldsymbol{u}^0\cdot d\boldsymbol{l} + \int_{t_0}^{t}\exp\left[-\frac{R}{H}\left(t-t'\right)\right]\frac{1}{H}\oint\frac{\boldsymbol{\tau}}{\rho H}\cdot d\boldsymbol{l}\,dt'$$

Circulation | Decaying contribution from initial state | Filtered surface stress

Can we describe Arctic Ocean circulation using linear dynamics?

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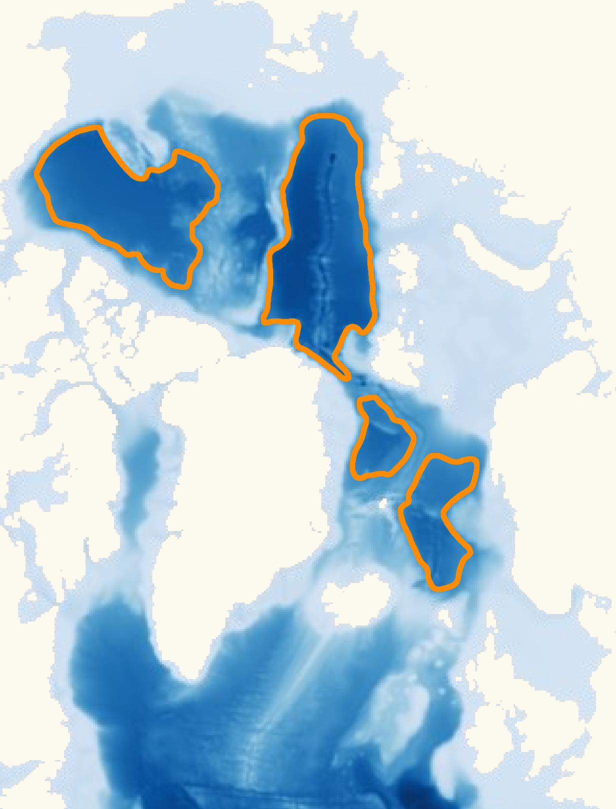

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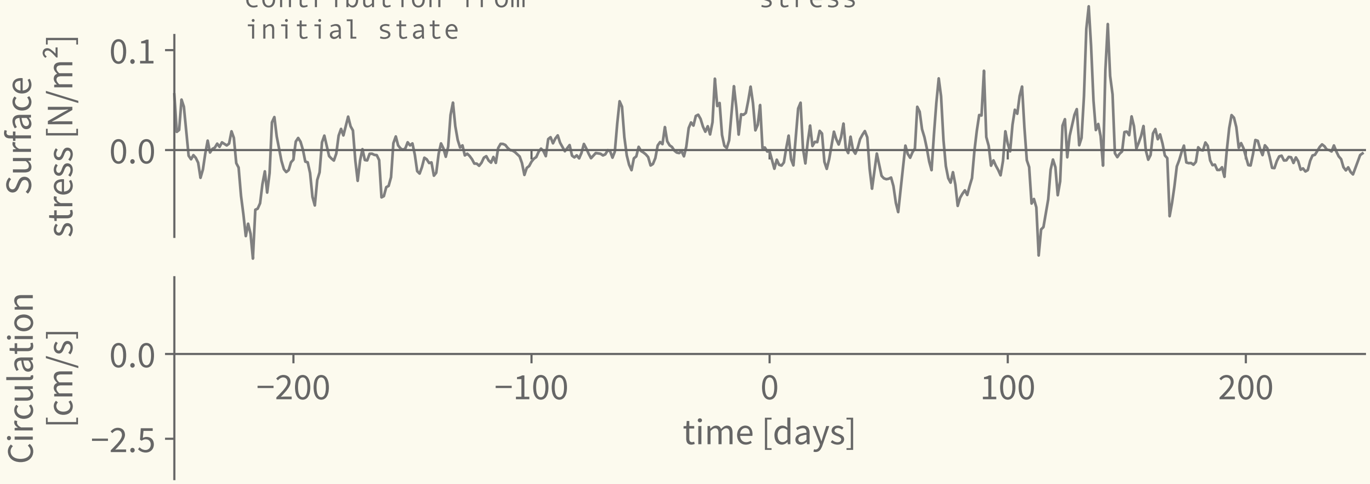
Circulation | Decaying contribution from initial state | Filtered surface stress



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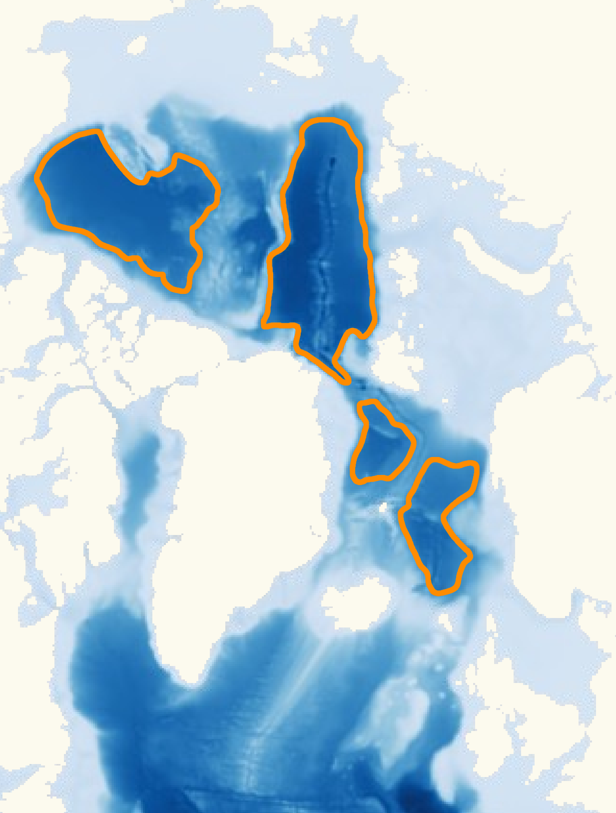

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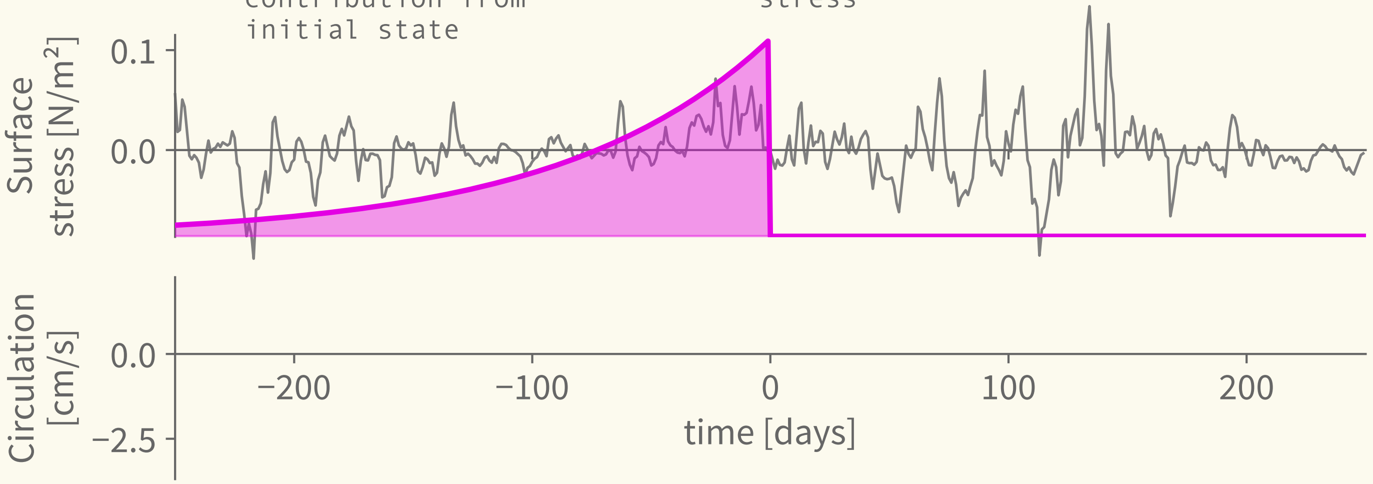
Circulation — Decaying contribution from initial state — Filtered surface stress



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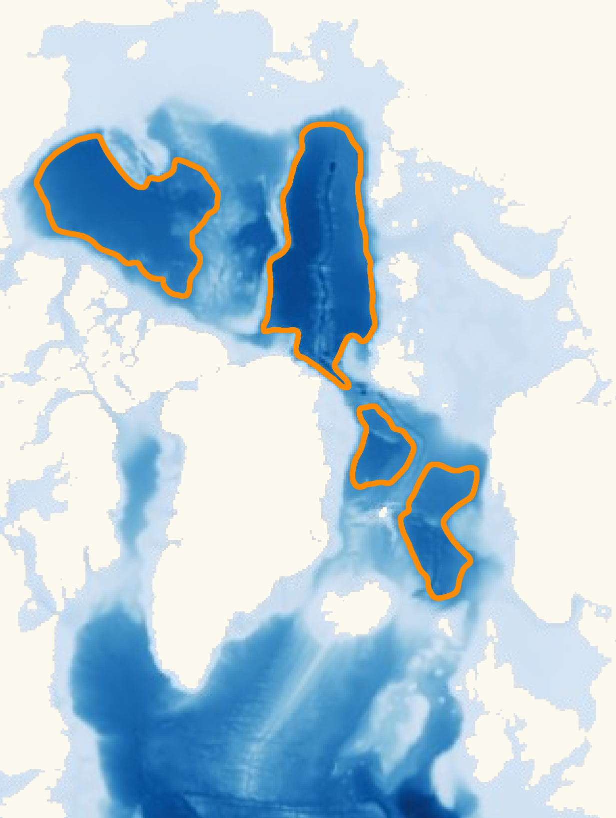

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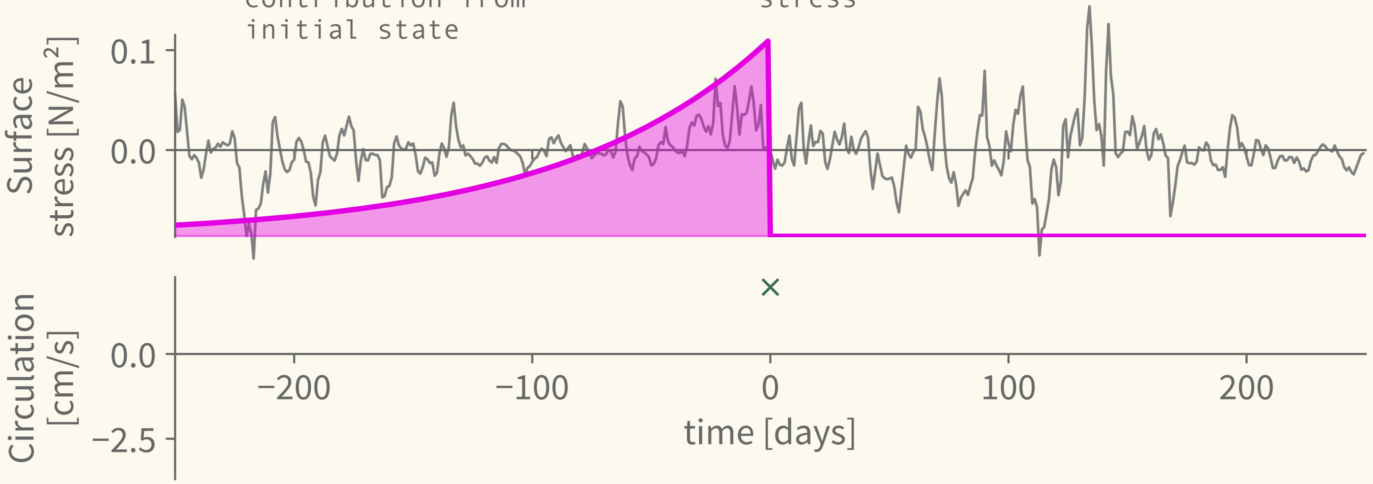

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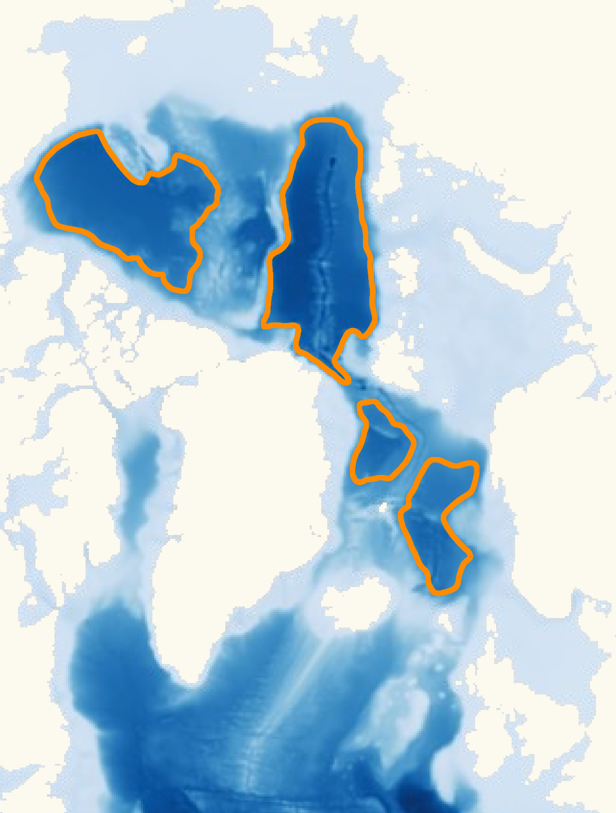

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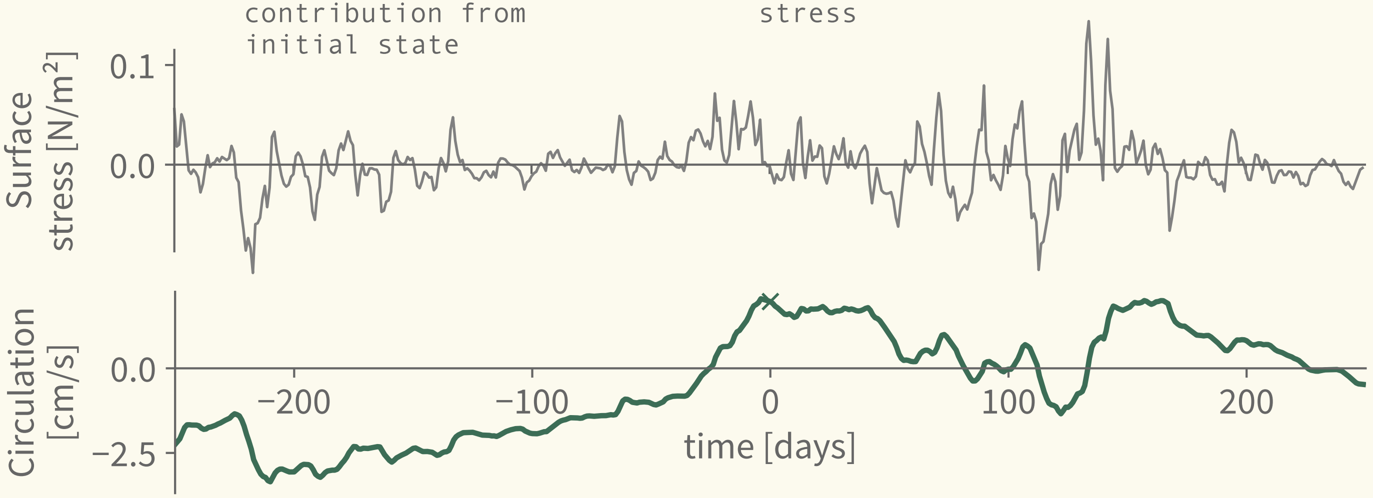

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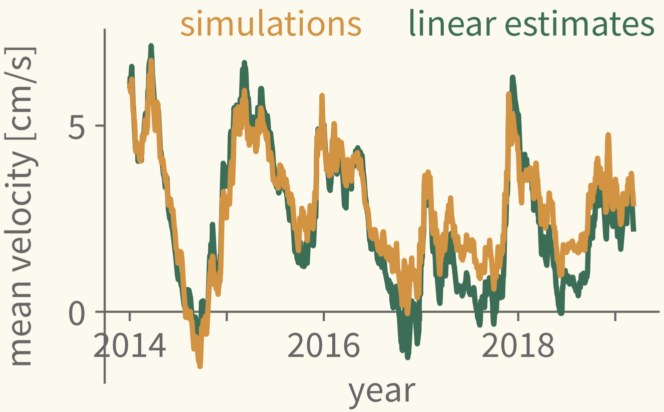

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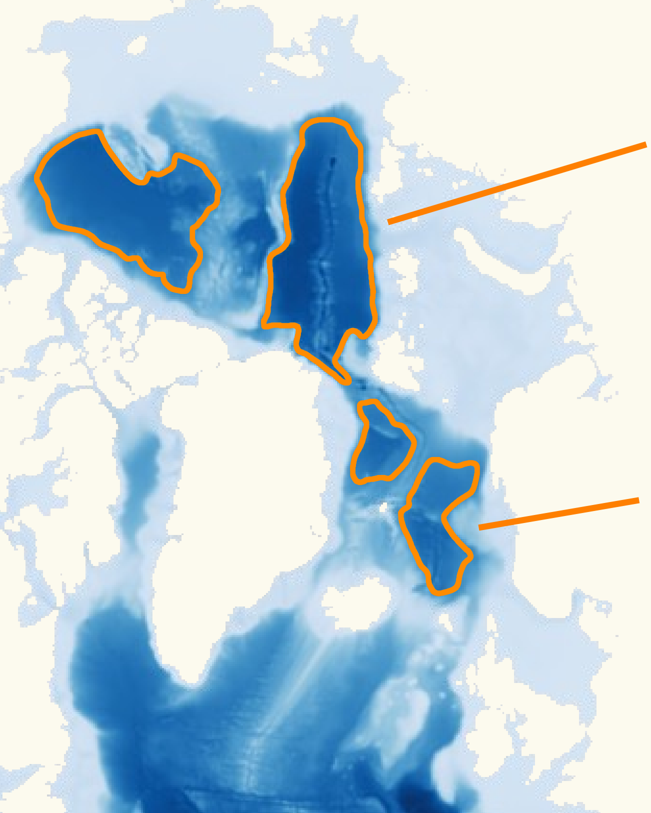

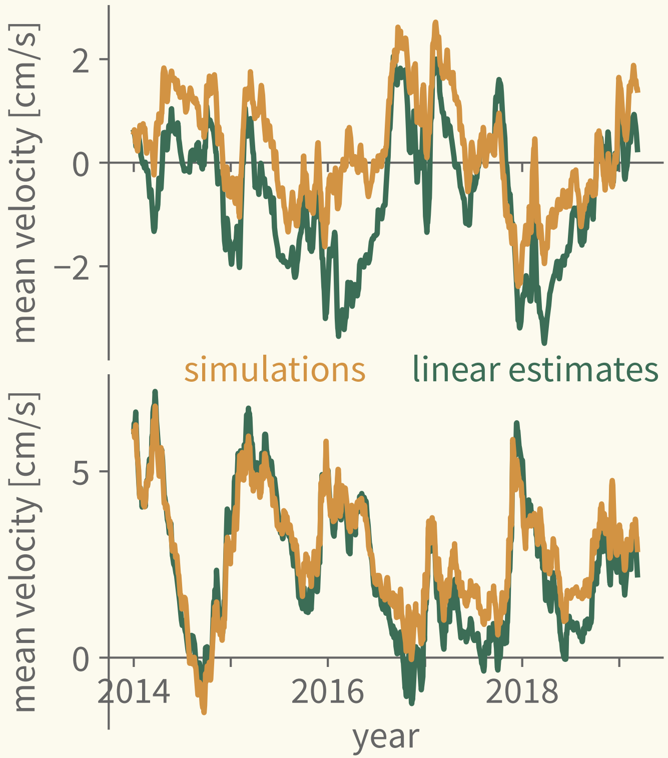

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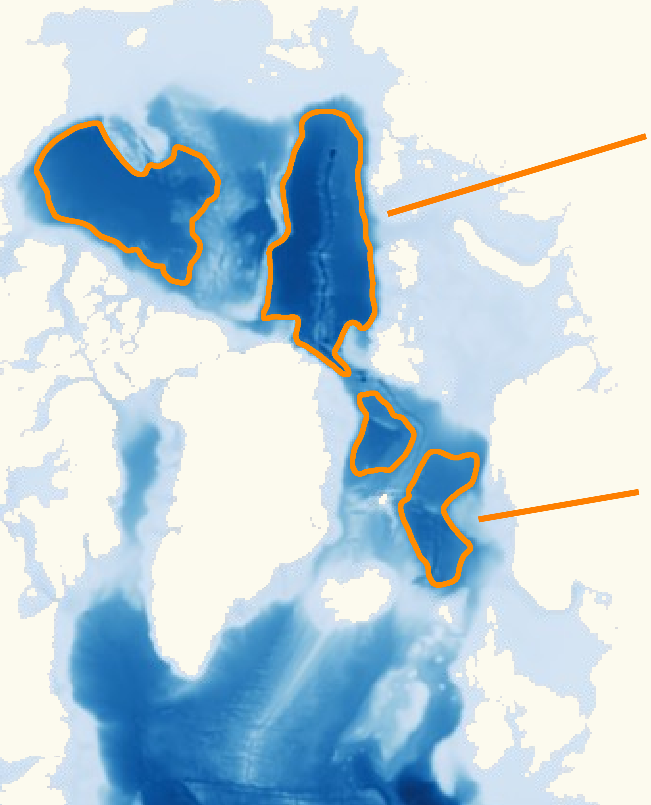

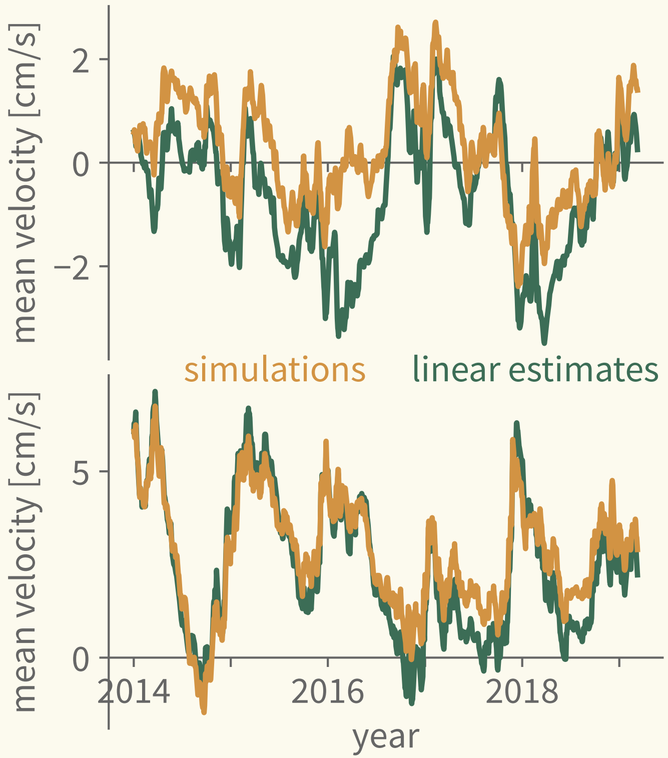

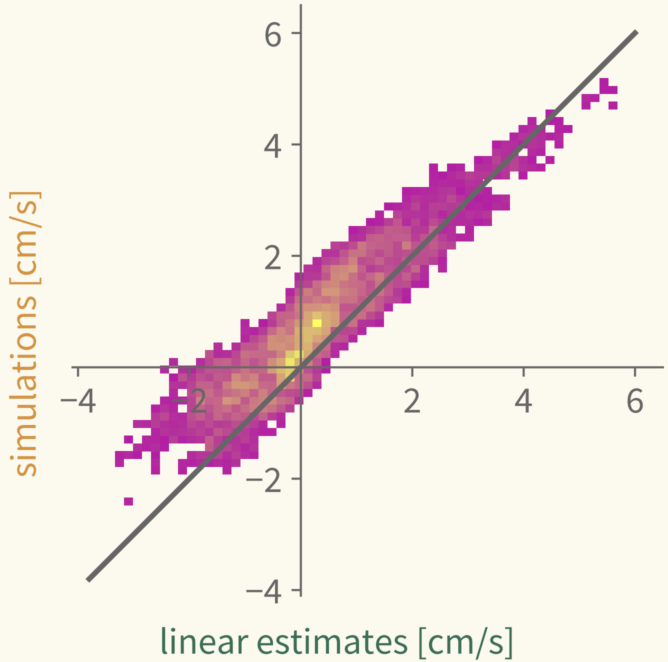

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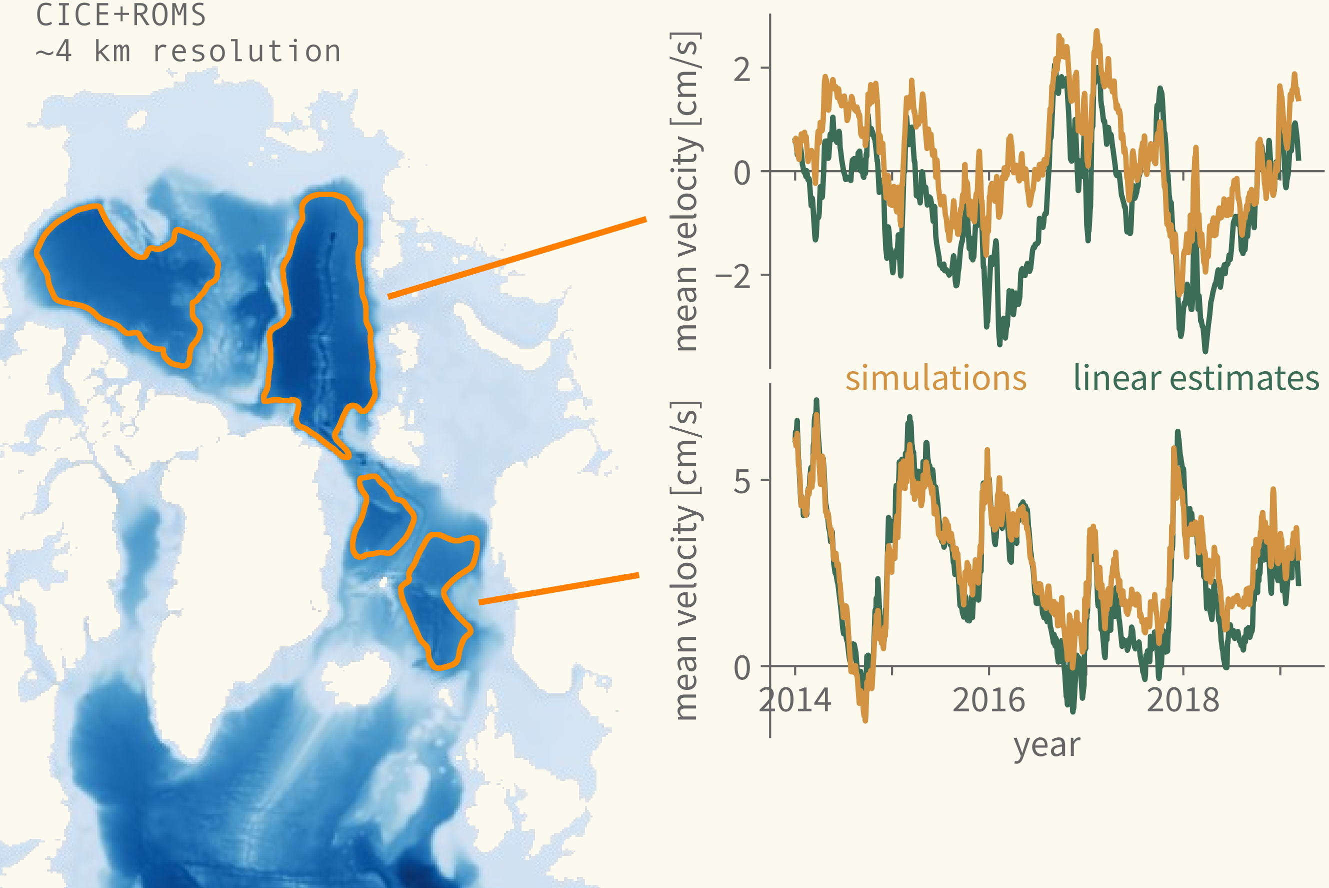
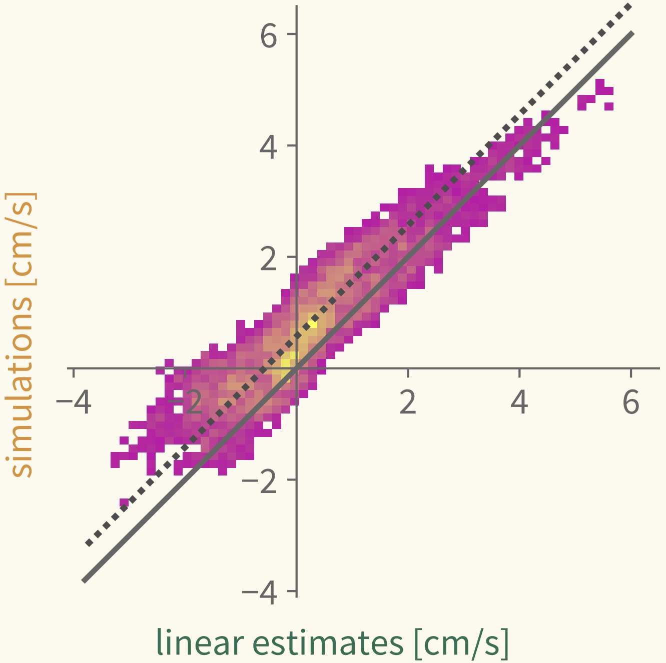
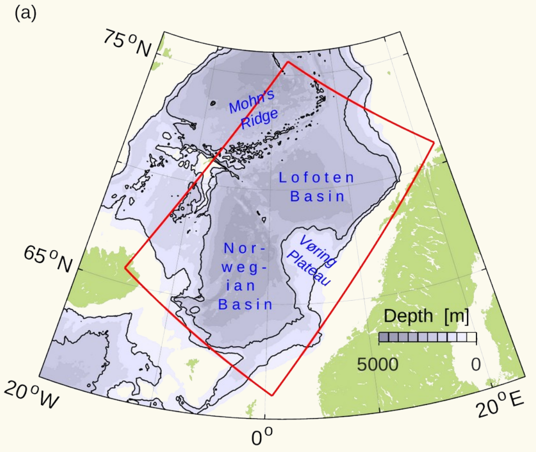


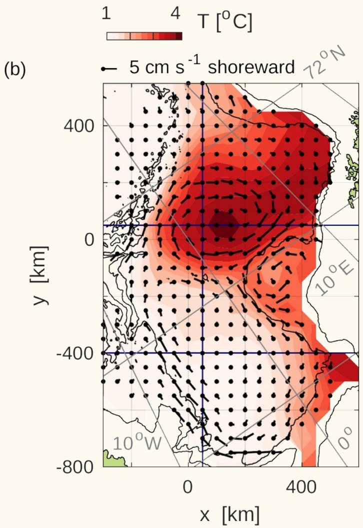


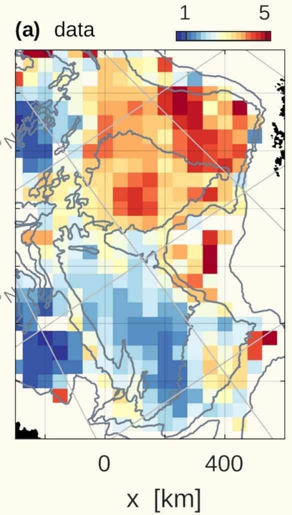
Link to article

Comparison with Lofoten Basin observations

Johnston et al.
(accepted)

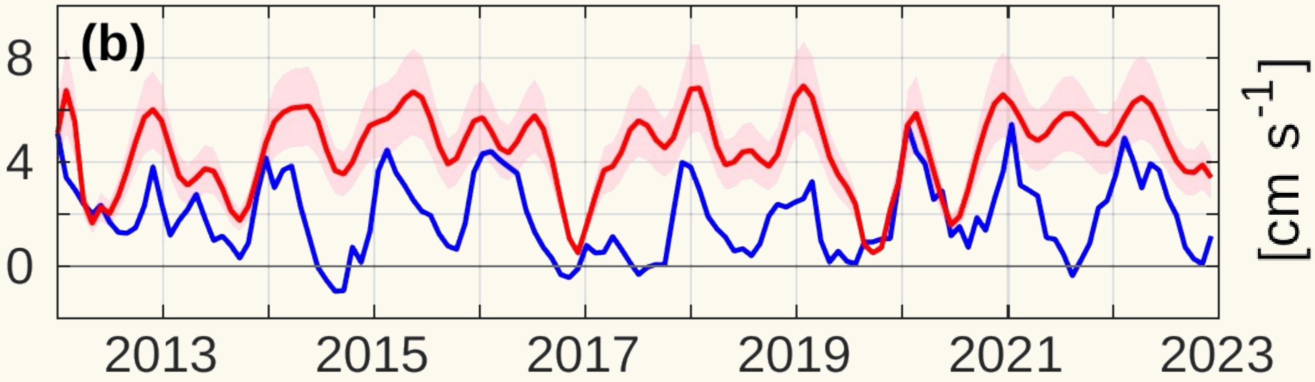






Observed circulation

Linear estimates



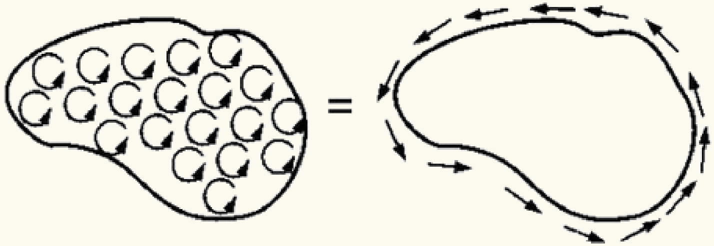
What enhances cyclonic circulation?

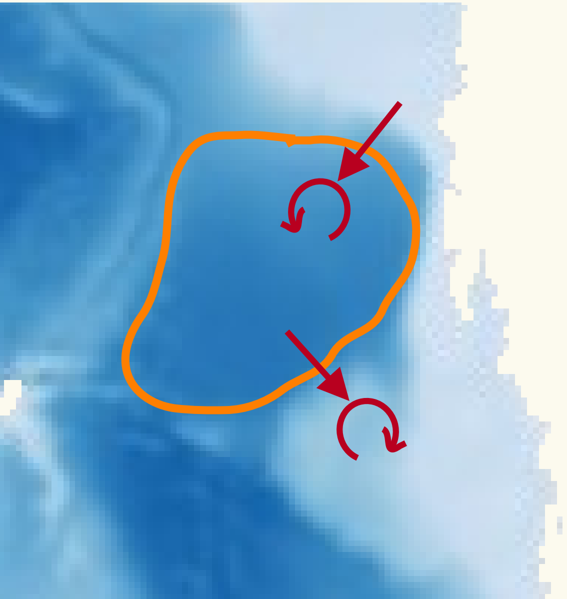
On depth contours, the main suspect is flux of vorticity

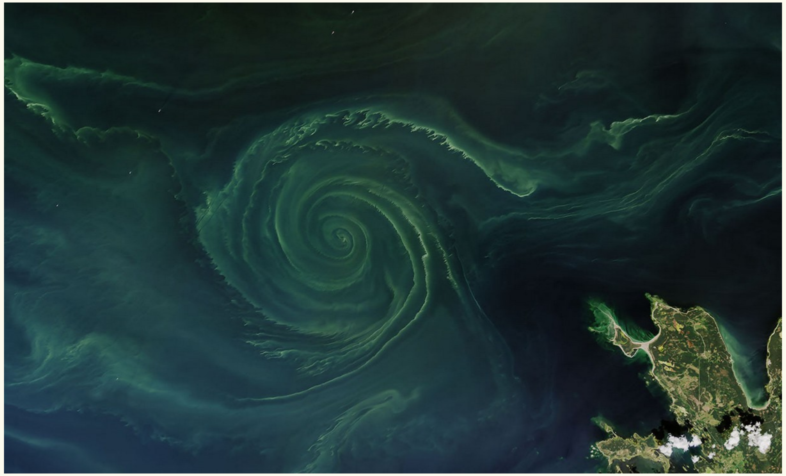
$$\frac{\partial}{\partial t}\oint \boldsymbol{u}\cdot d\boldsymbol{l} = \oint \frac{\boldsymbol{\tau}}{\rho H}\cdot d\boldsymbol{l} - \oint \frac{R}{\rho H}\boldsymbol{u}\cdot d\boldsymbol{l} - \oint \overline{\zeta \boldsymbol{u}}\cdot \boldsymbol{n}\, dl$$

Change in circulation	Surface stress	Bottom drag	Flux of vorticity

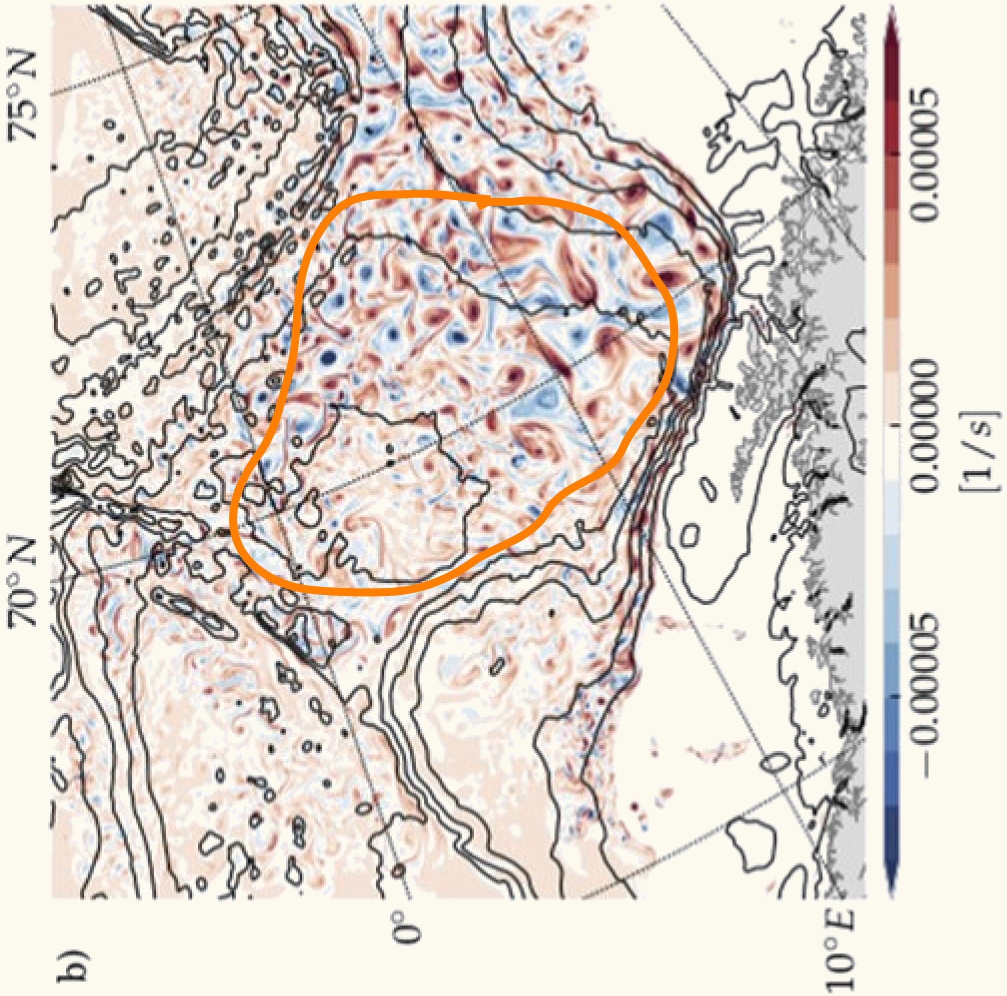
Green's theorem







Vorticity flux contribution in simulations

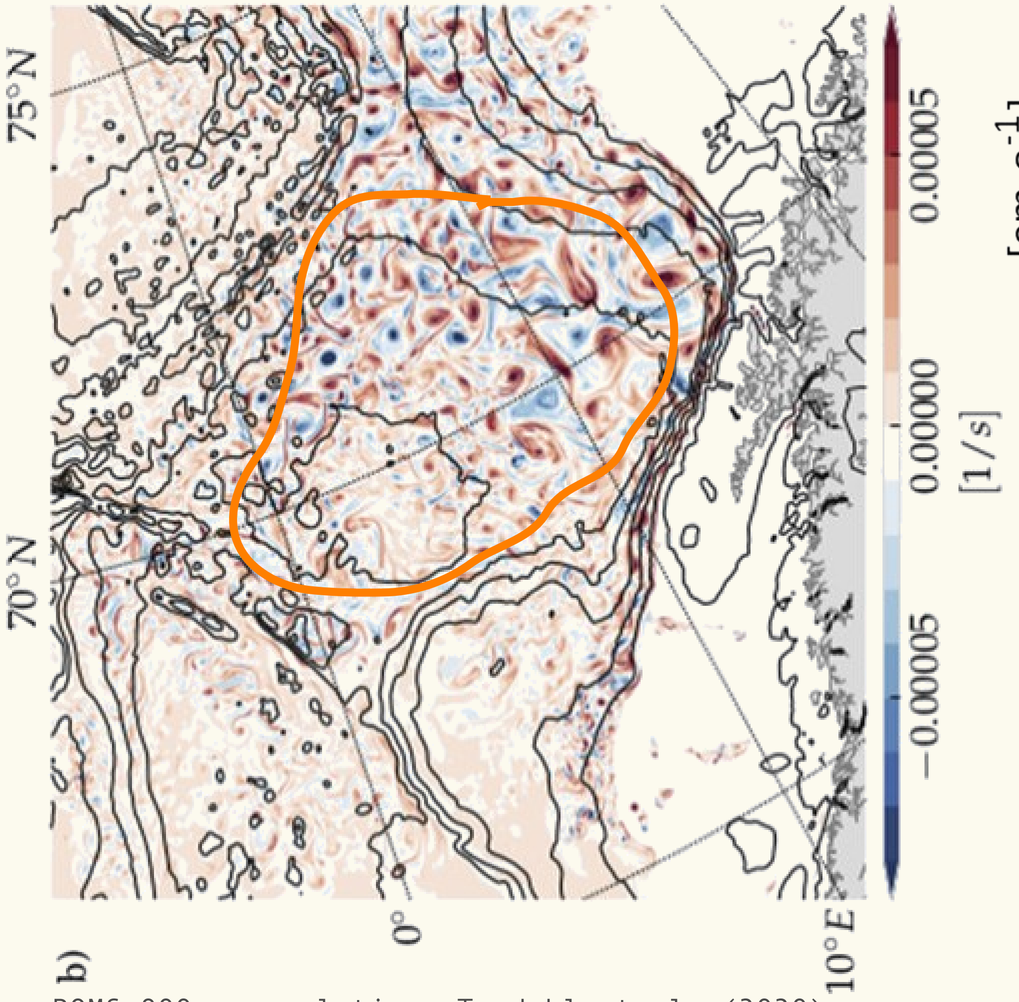


ROMS 800 m resolution, Trodahl et al. (2020)

$$\frac{\partial}{\partial t}\oint \boldsymbol{u}\cdot d\boldsymbol{l} = \oint \frac{\boldsymbol{\tau}}{\rho H}\cdot d\boldsymbol{l} - \oint \frac{R}{\rho H}\boldsymbol{u}\cdot d\boldsymbol{l} - \oint \zeta \boldsymbol{u}\cdot \boldsymbol{n}\, dl$$

Change in circulation | Surface stress | Bottom drag | Flux of vorticity

Vorticity flux contribution in simulations



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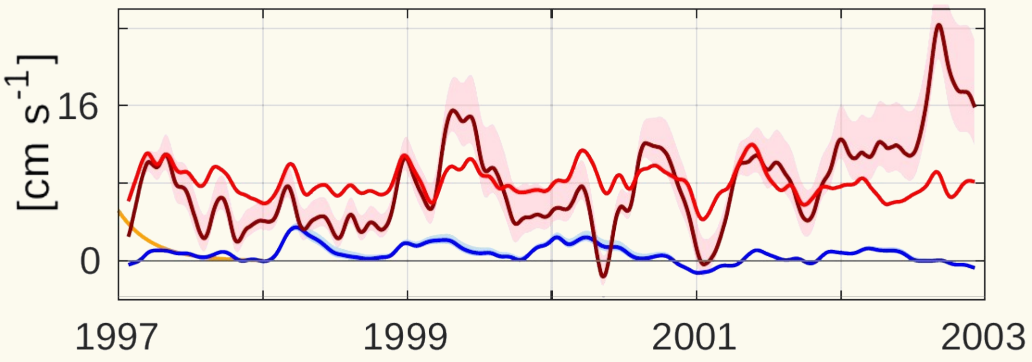
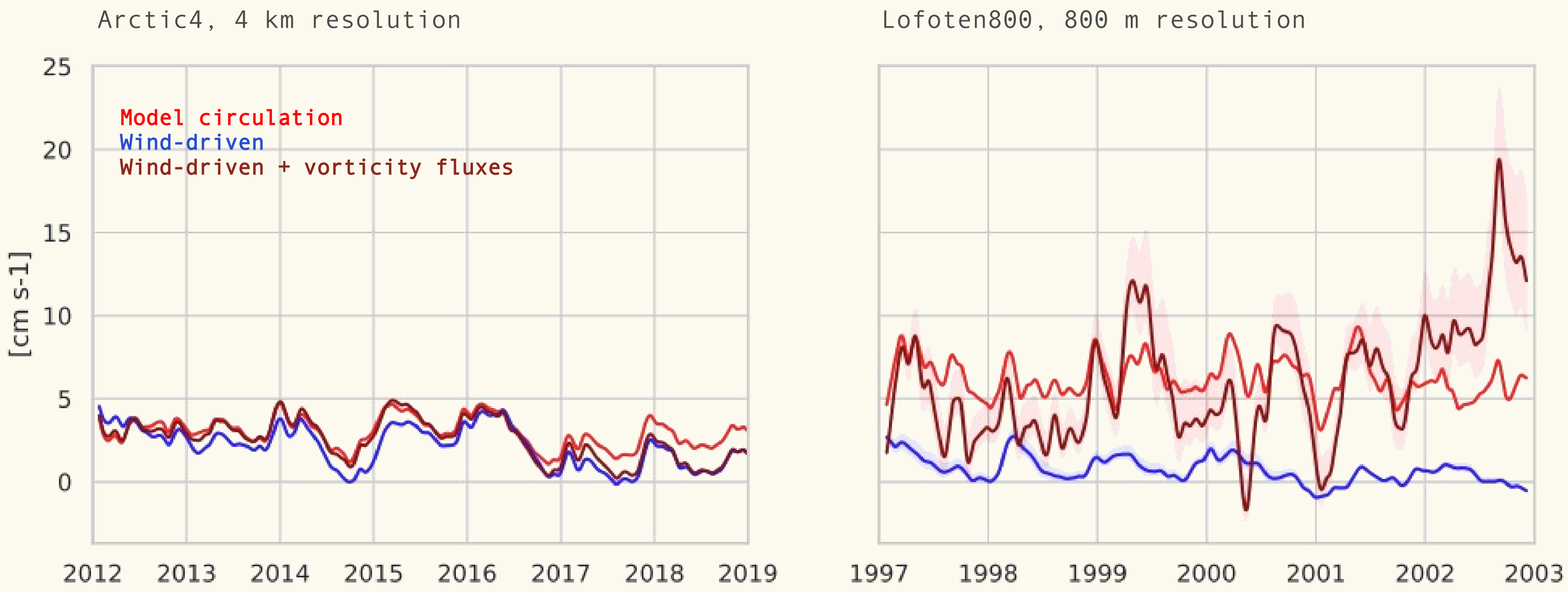


Lofoten800 circulation
Wind-driven
Wind-driven + vorticity fluxes

$$\frac{\partial}{\partial t}\oint \boldsymbol{u}\cdot d\boldsymbol{l} = \oint \frac{\boldsymbol{\tau}}{\rho H}\cdot d\boldsymbol{l} - \oint \frac{R}{\rho H}\boldsymbol{u}\cdot d\boldsymbol{l} - \oint \zeta \boldsymbol{u}\cdot \boldsymbol{n}\, dl$$

Change in circulation	Surface stress	Bottom drag	Flux of vorticity

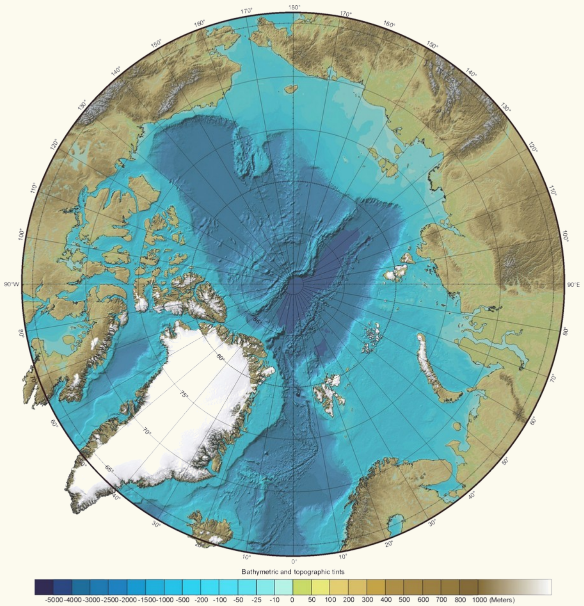
The need for high resolution

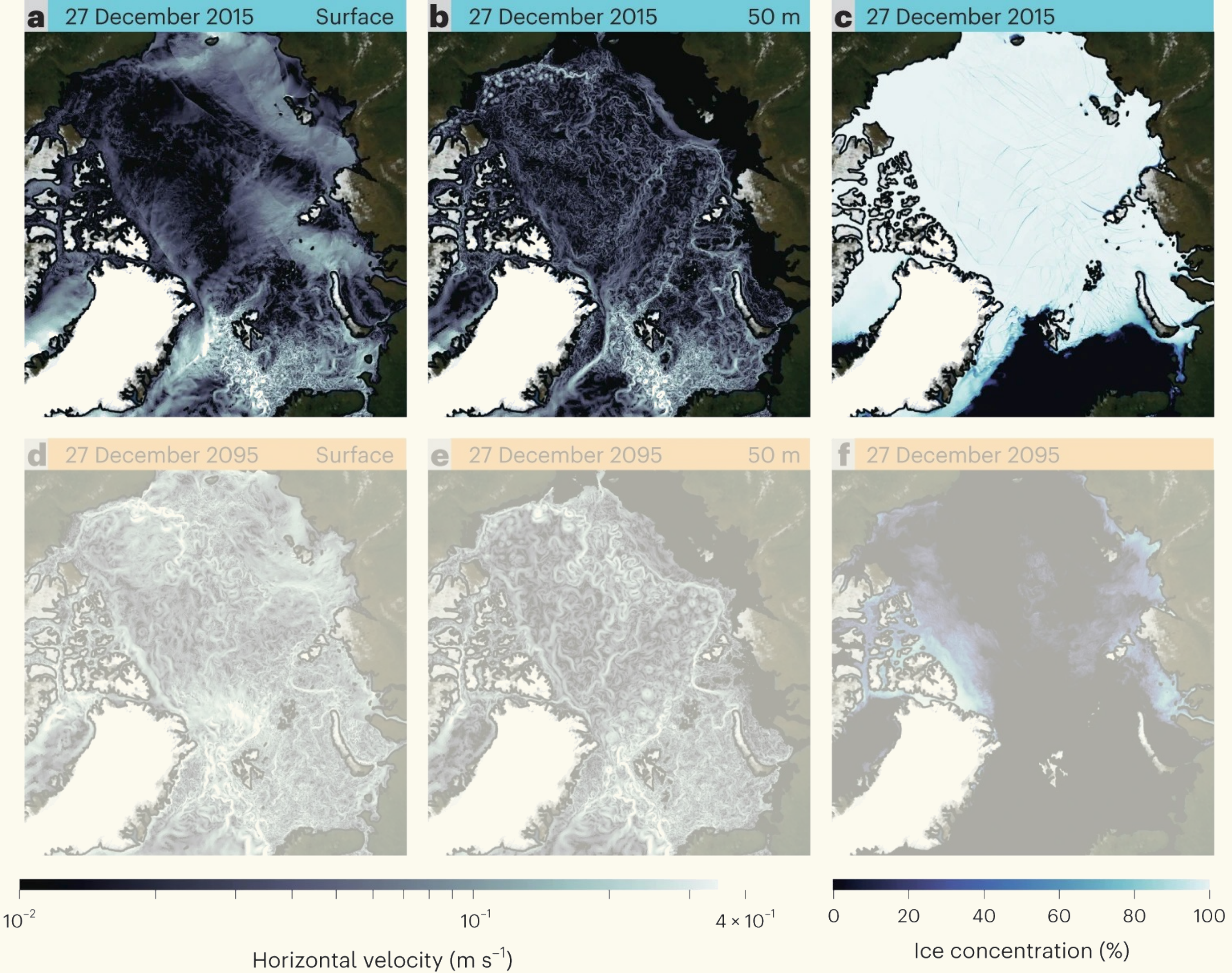


Blue Arctic

Li et al. Nature C. (2024)

FESOM2, 1 km resolution





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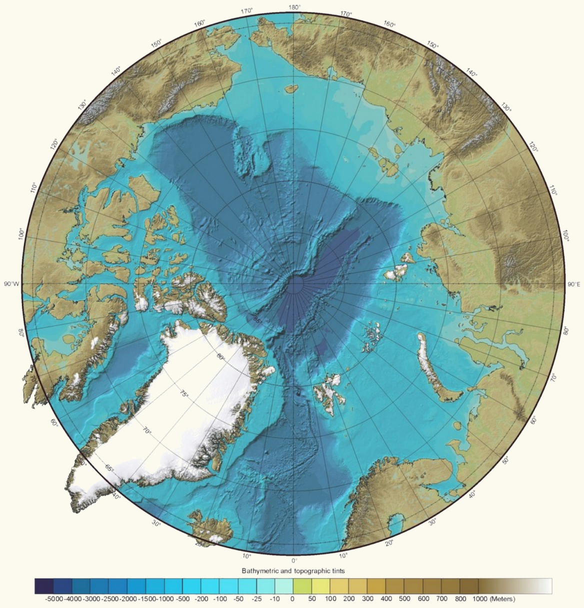
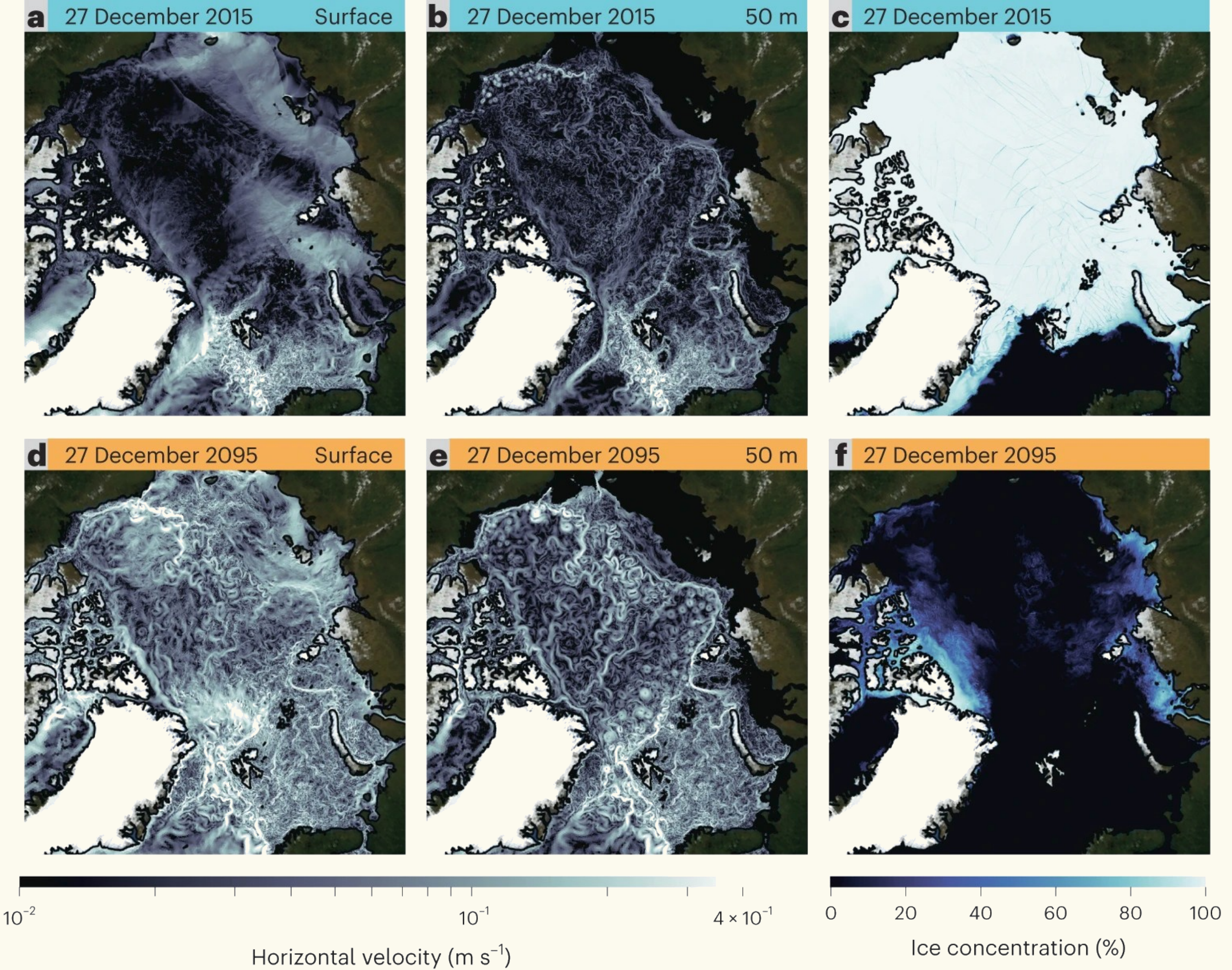
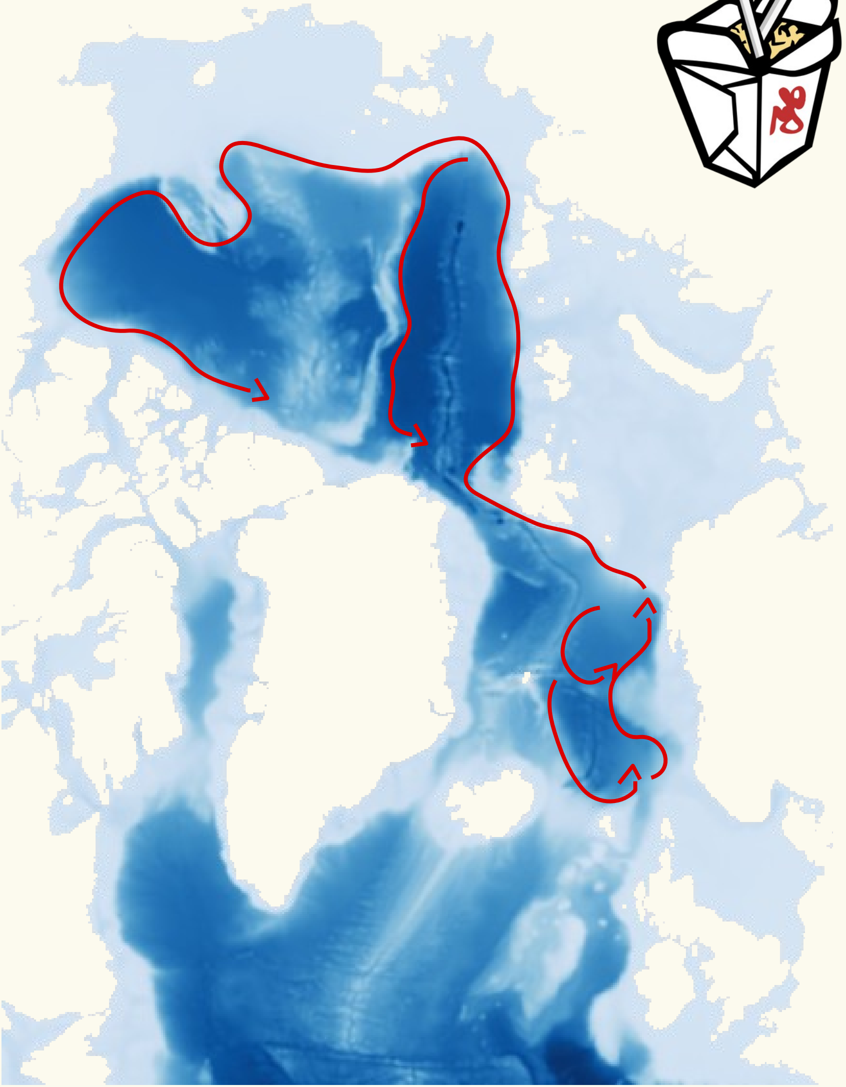
Li et al. Nature C. (2024)

FESOM2, 1 km resolution



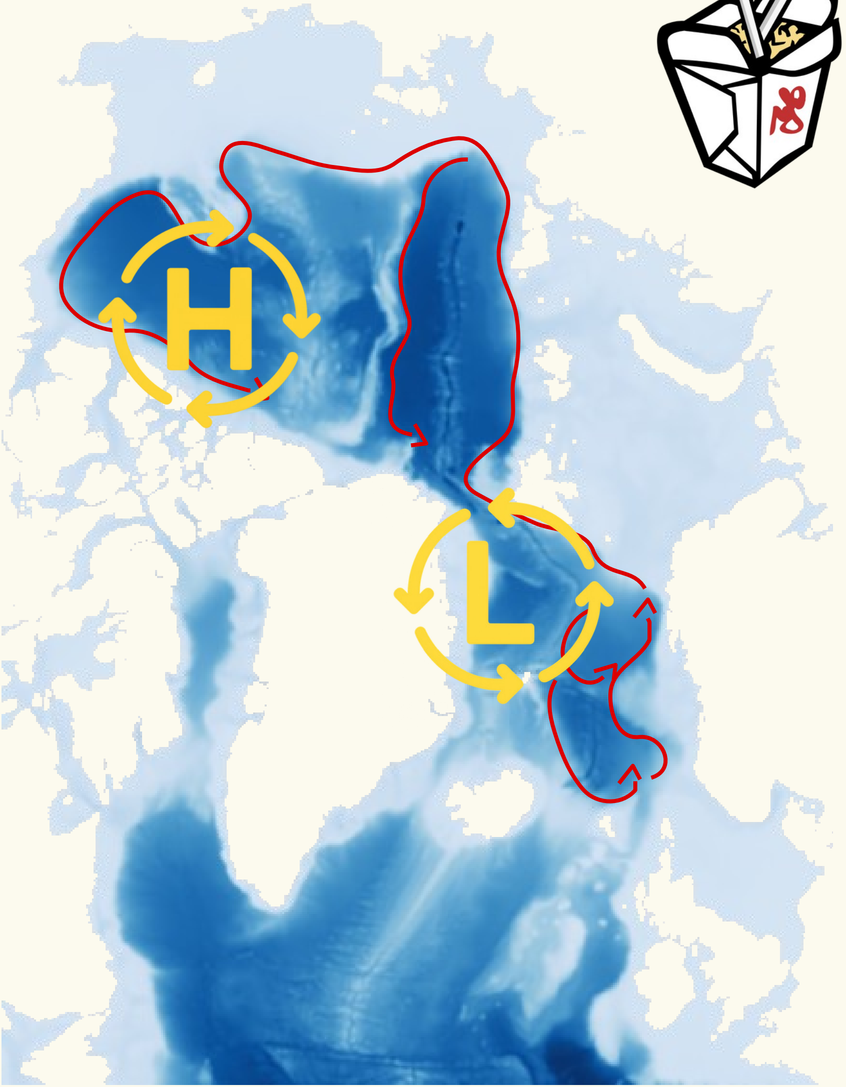


Take away



Take away

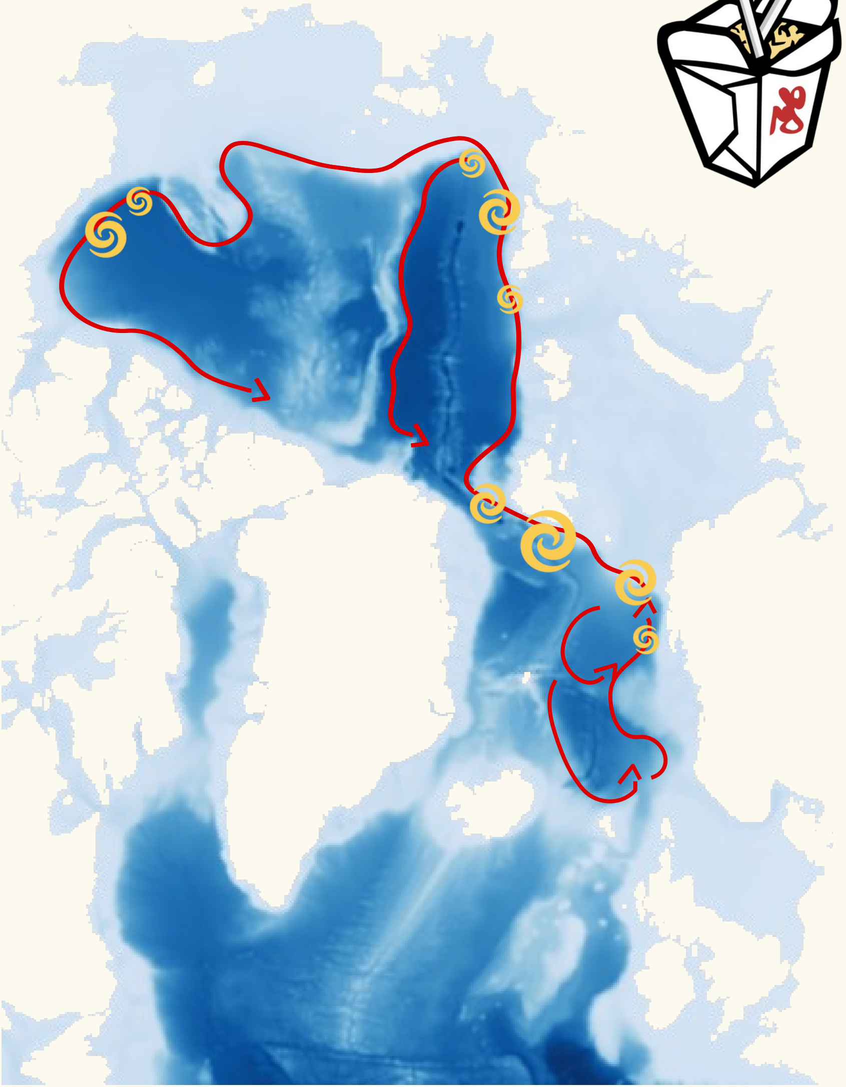
Circulation responds, to a large degree, linearly to surface stress.



Take away

Circulation responds, to a large degree, linearly to surface stress.

However, vorticity fluxes connected to eddy activity gives a positive shift.



Take away

Circulation responds, to a large degree, linearly to surface stress.

However, vorticity fluxes connected to eddy activity gives a positive shift.

Very high resolution is needed to properly simulate positive shift.