Sea ice modelling in the twenty-first century: versatile parameterisations from physics!

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Thanks to: Adam Bateson, Daniela Flocco, Harry Heorton, David Schroeder, Michel Tsamados, Alex Wilchinsky

The exam questions

- **How should we design a climate model to obtain better predictions of polar climates on timescales of decades?**
- **How can we integrate observations better with models?**
- **What additional observations would help improving models?**

Modelling sea ice in climate models

Sea ice models are formulated as **continuum** expressions of **local balances of momentum, mass, and heat.** The **state variable** is **thickness distribution**.

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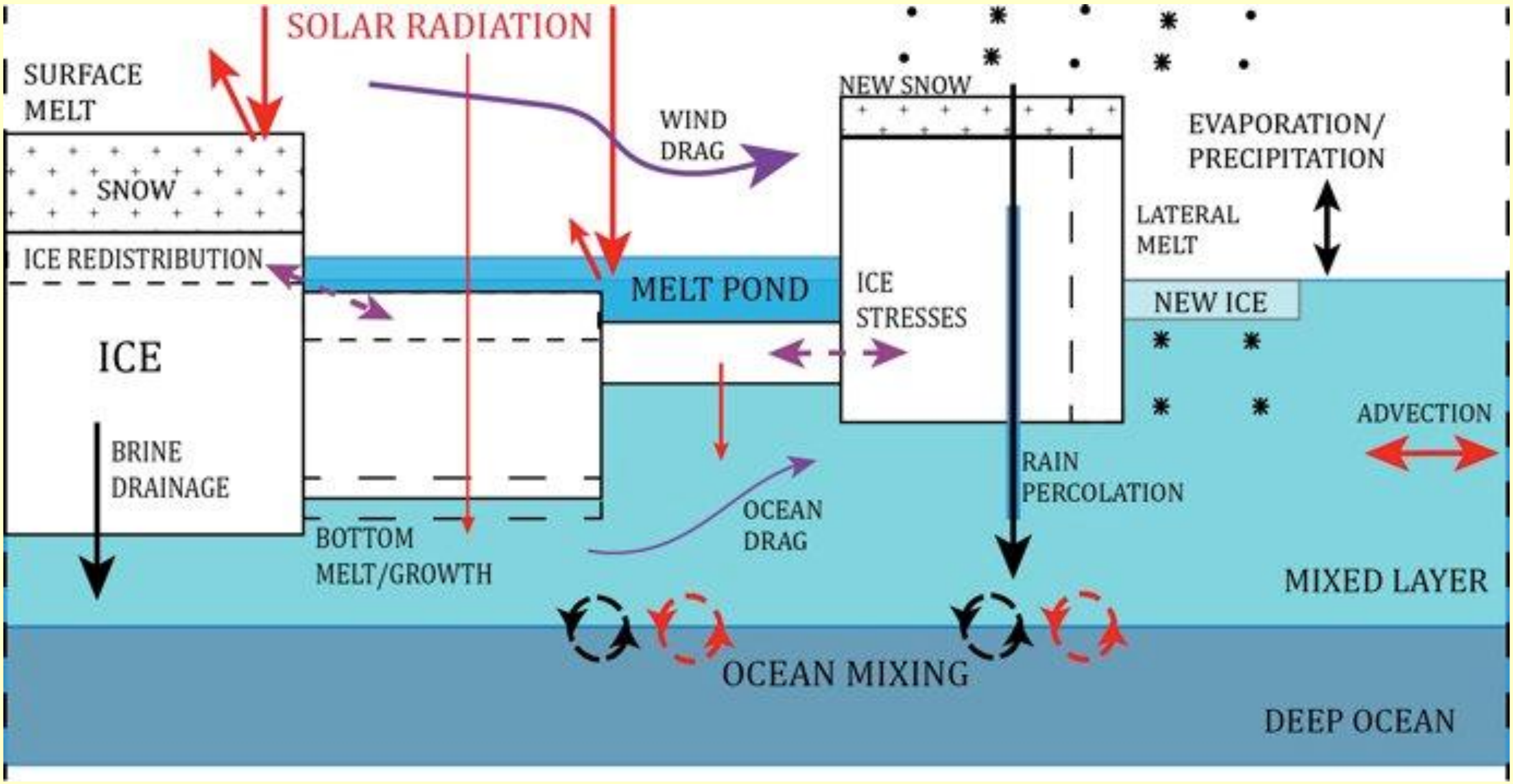

[Petty et al, 2012]

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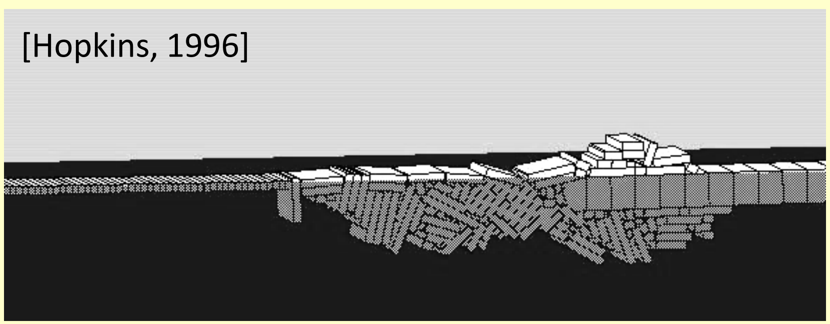
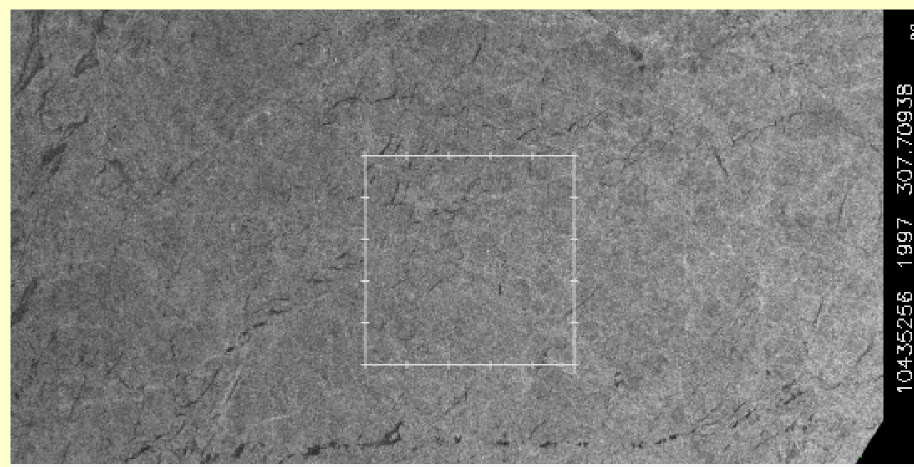
- **Dynamic** processes, which control the motion of ice cover, deformation, and redistribution of thickness. Example processes are air and ocean drag, ridging, sliding, and rupture (rheology).



[Hopkins, 1996]



[Kwok, 2001]

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Wettlaufer, Worster, Huppert 1997

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Dynamic and thermodynamic processes are typically **closely connected** and involve interactions with the atmosphere and ocean.

Many of these processes are represented in climate sea ice models with **parameterisations**, simplified representations that work within the technical constraints of climate models.

A sea ice lead, formed in divergence, results in rapid new ice growth.

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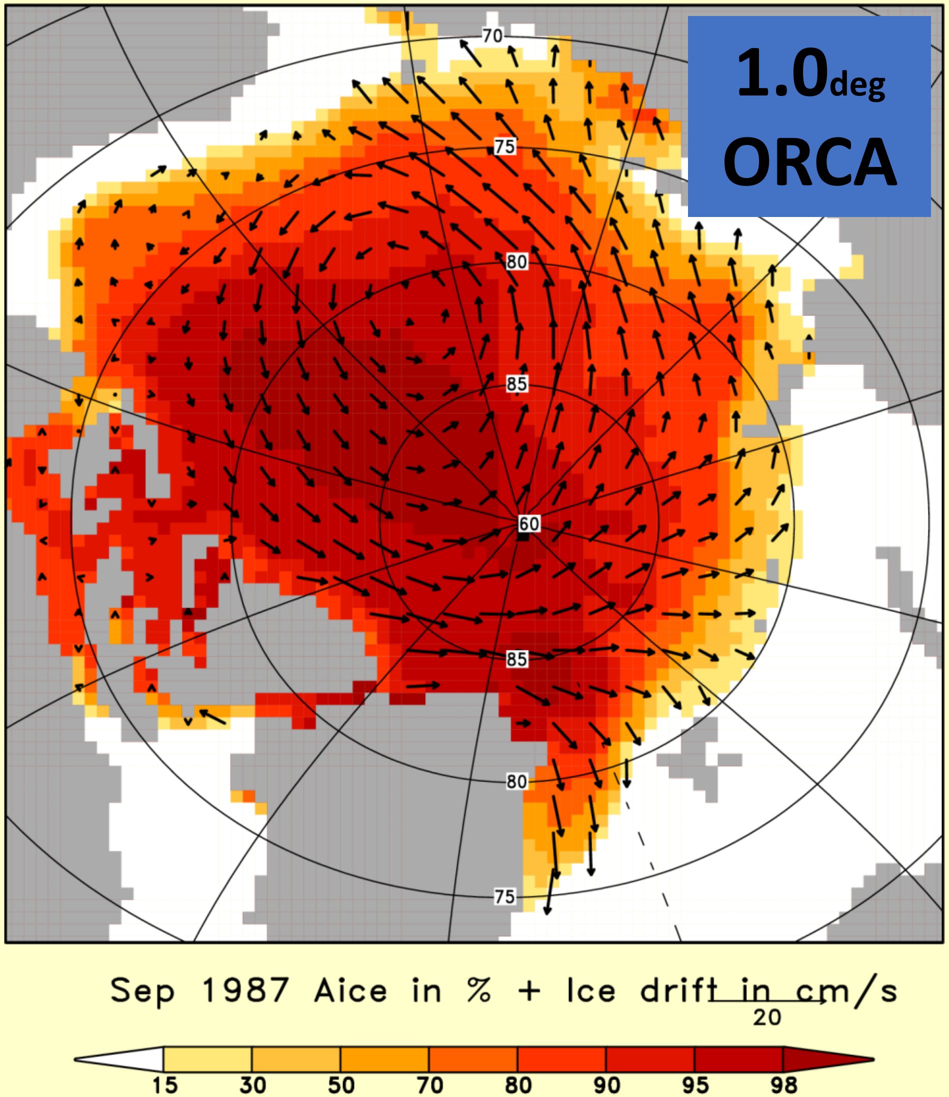
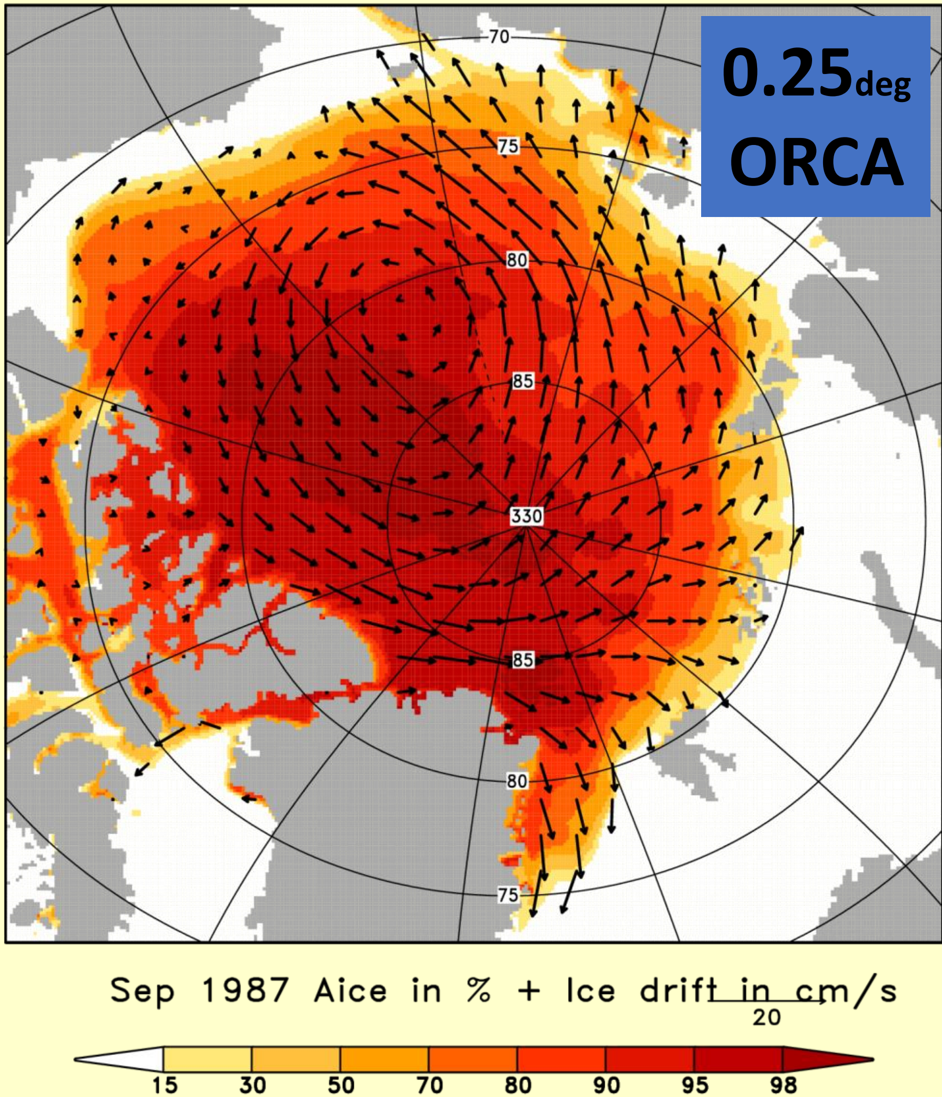
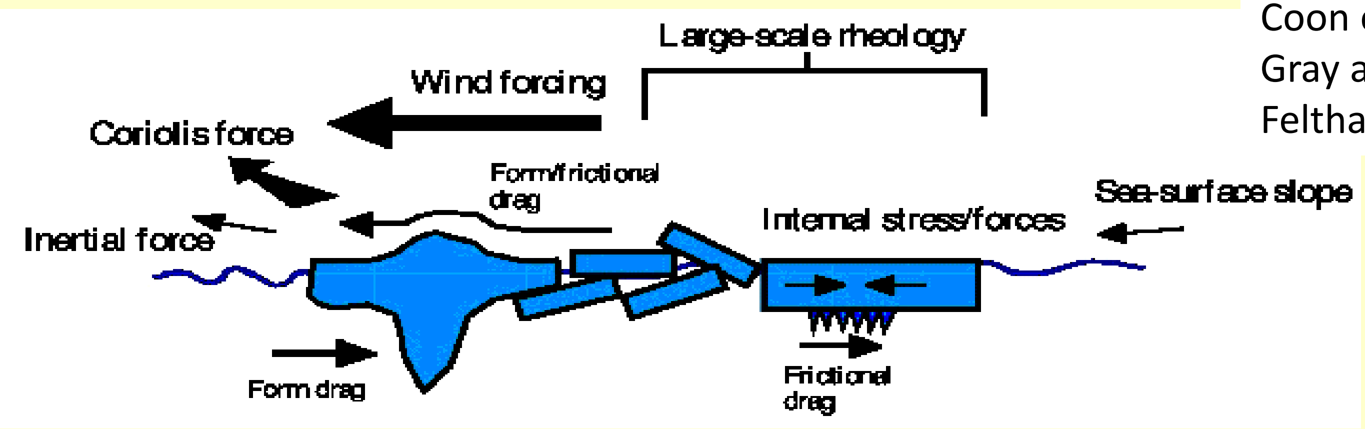
- By contrast, **once the equations are solved properly** (and land masks **resolved**), increasing the sea ice model resolution is **not** expected to result in fundamentally different model behaviour…





Finer resolution sea ice model (right) but with same resolution air and ocean forcing.

Horizontal momentum balance of sea ice



Coon et al. (1974);
Gray and Morland (1994);
Feltham (2008)

Vertically-integrated (i.e. horizontal) momentum balance is:

$$\frac{\partial \boldsymbol{u}}{dt} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = \frac{\boldsymbol{\tau_a}}{m} + \frac{\boldsymbol{\tau_w}}{m} + \frac{1}{m} \nabla \cdot \boldsymbol{\sigma} - f\boldsymbol{k} \times \boldsymbol{u} - g \nabla \boldsymbol{h}$$

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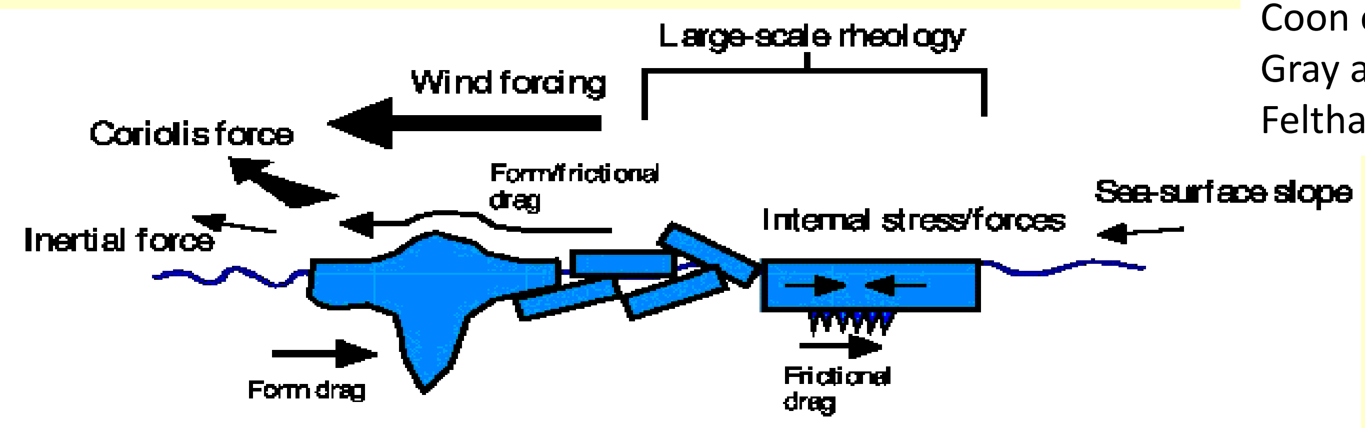

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~5x10^{-7} ~5x10^{-5} ~5x10^{-5} ~5x10^{-5} ~5x10^{-6} ~5x10^{-6} ms^{-2}

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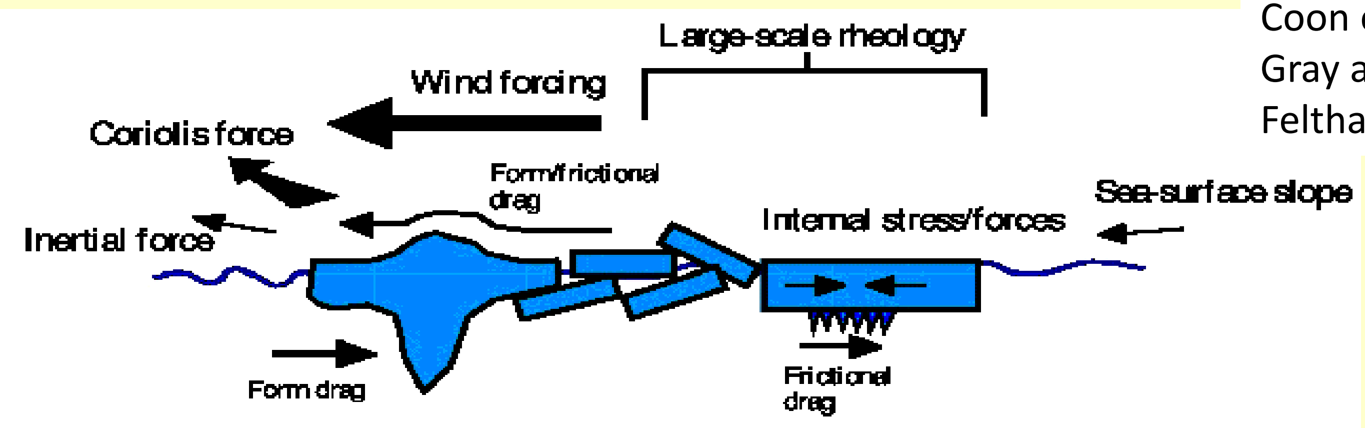

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$$Re \equiv \frac{\text{advection}}{\text{friction}} \sim \frac{\text{advection}}{\text{internal stress}} \sim 0.001$$

i.e. no turbulence,
no eddies,
no internal variability

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…to do this, we need **realistic parameterisations** (representations of sub-grid scale physics).

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A: Higher fidelity and higher resolution atmosphere and ocean models are needed to provide boundary forcing and resolve feedbacks with the sea ice cover.

While **understanding** of broad exchanges of heat, mass, and momentum may be achieved with current (or simpler) models, to improve **predictive** ability of the **sea ice model**, my focus would be on developing realistic, and **versatile** (future-proof) **parameterisations** of processes important now and in the future.

What should we parameterise?

- **Numerical experiments** demonstrate areas where sea ice model physics uncertainty matters to large scale metrics of the ice cover, atmosphere and ocean.
- **Fully coupled** models contain **too much variability** to cleanly isolate particular processes but **uncoupled** models can **overestimate/underestimate** the importance of processes due to absence of feedbacks, e.g. ice-ocean mixed layer interaction.
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- At leading order **thermodynamic** parameterisations, e.g. snow metamorphosis, melt ponds, brine drainage, snow blow off, primarily affect **growth/loss** of ice and **dynamic** parameterisations, e.g. rheology, drag, primarily affect the **distribution/motion** of ice, including ice export. [YES, there are many exceptions..]
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- While the literature contains **many sensitivity** studies, analysis of (non-radiative) air-sea ice-ocean **feedbacks** is **lacking** [Goosse et al, 2018].
- **Structural uncertainty** limits what we can learn about relative importance of processes, e.g. complete absence of a class of processes such as wave-ice interaction. Structural uncertainty can also arise from the model type, e.g. continuum vs discrete.
- **Elimination** of structural uncertainty, and **details** of process parameterisations must be guided by **observations**.

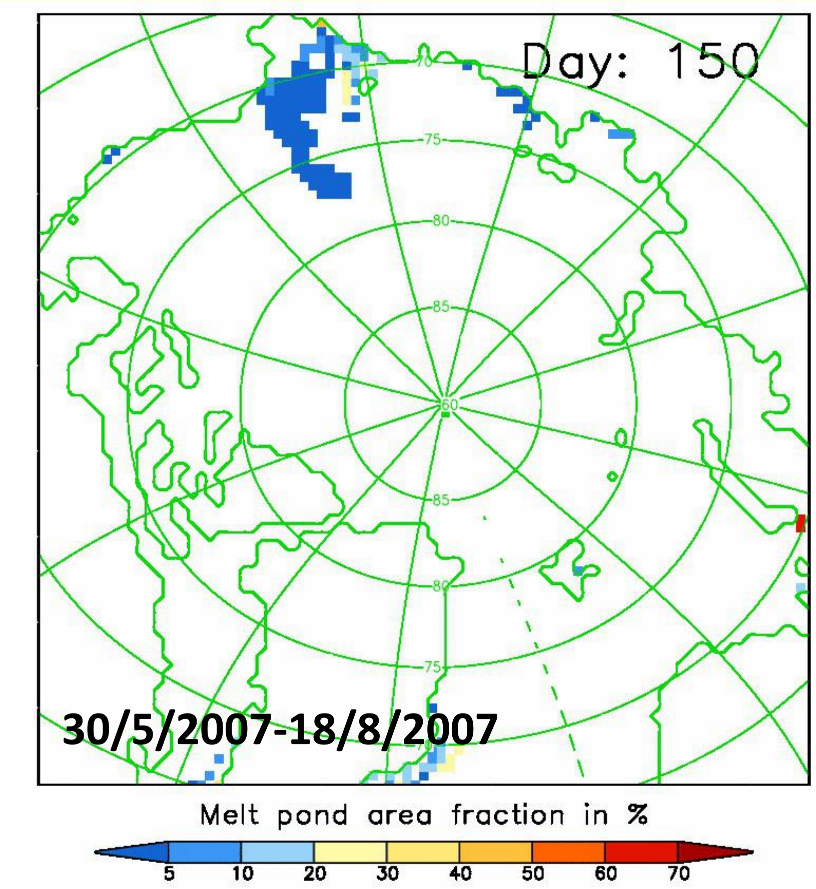
What new parameterisations likely to become more important to sea ice in the coming decades?

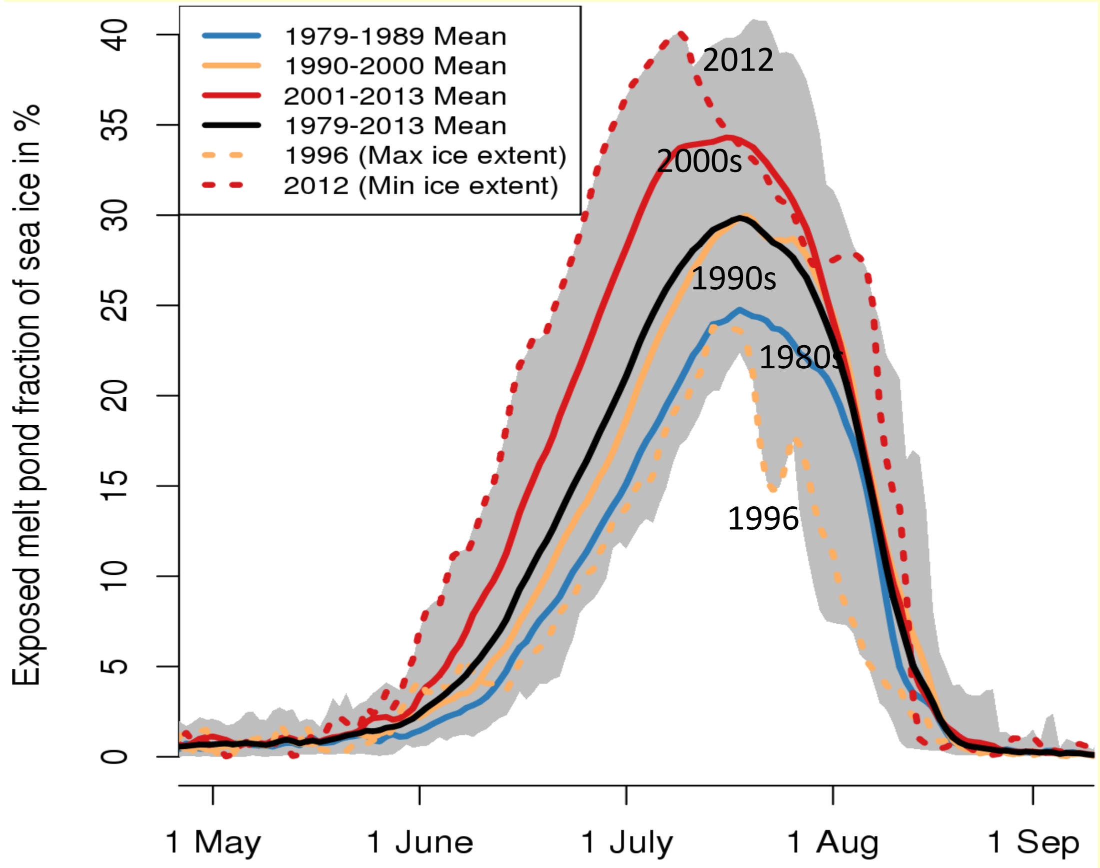
- **Melt ponds** - the summer pond coverage is increasing and this affects albedo

Melt ponds

- Surface snow/ice melt accumulates in ponds (1-100m wide, 0.1-1.5m deep).
- Pond area coverage ranges from 5—50%.
- Ponded ice albedo (0.15—0.45) < Bare ice/snow albedo (0.52—0.87)
- My group [Flocco et al, 2007; 2010; 2012; 2015] developed melt pond parameterisation now included in CICE sea ice model and some CMIP6 models.
- Basic parameterisation features:
  - Pond volume collects on ice of lowest height and pond volume treated as a tracer.
  - Hydrostatic balance is maintained throughout.
  - Vertical drainage is by Darcy’s law with a variable permeability.

Melt pond area evolution over the decades



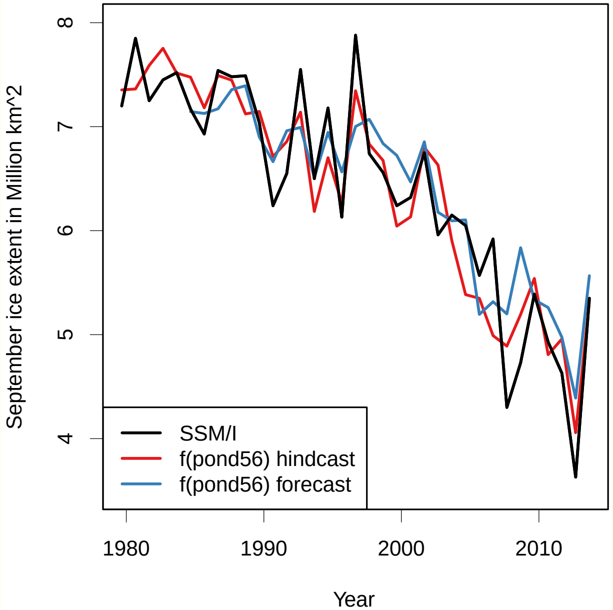


Strong, negative correlation between the **modelled** early melt season pond fraction and the **observed** September sea ice extent minima.

Melt ponds and climate prediction

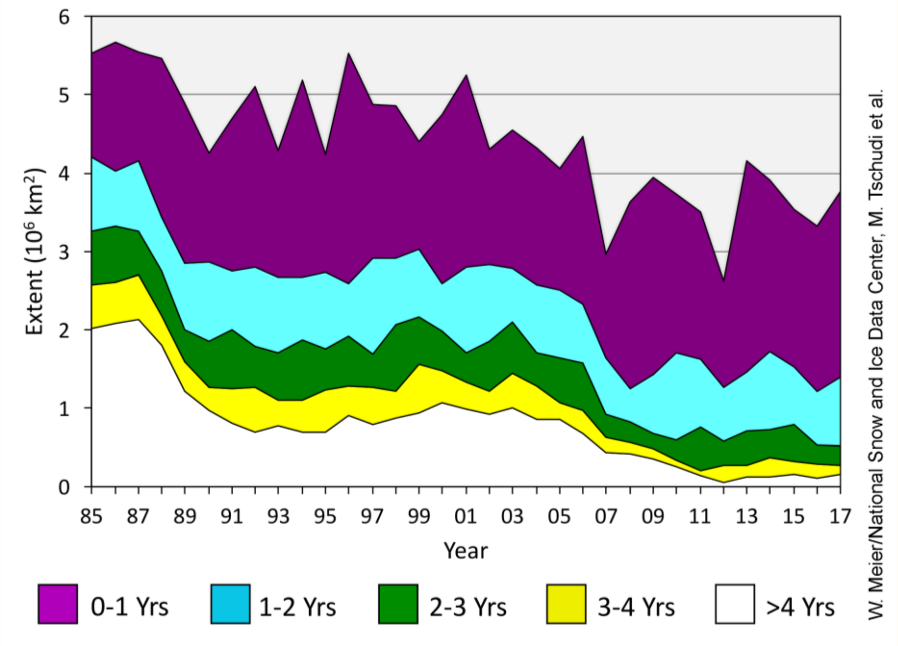
- *Seasonal predictability:*

Melt ponds have made it possible to make **skilful forecasts** of September sea ice minima more than 2 months in advance, using melt pond cover. [Schroeder et al, NCC, 2014]



- *Decadal variability/predictability:*

- Younger ice is flatter than older ice and the same pond volume leads to greater pond area.
- The fraction of younger ice is increasing.
- Even with **no change** in radiative forcing, atmospheric or oceanic conditions, the change in sea ice topography alone will result in **greater sea ice melt**.



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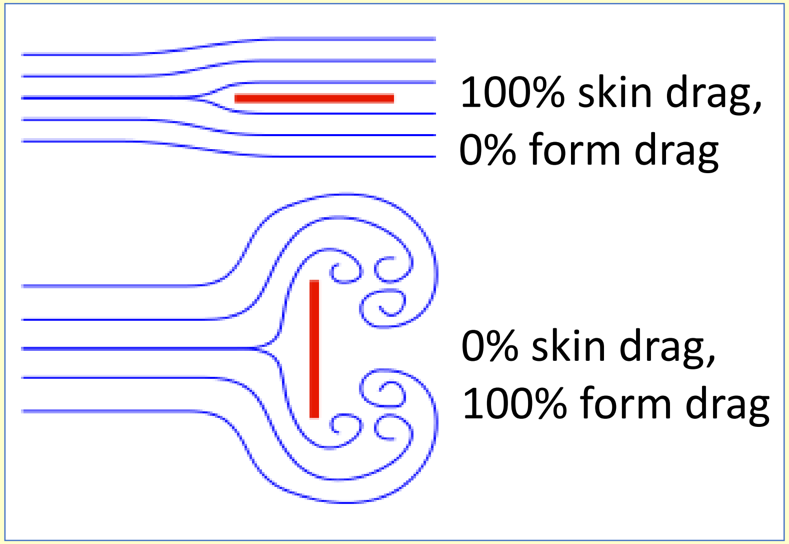
Form drag over sea ice

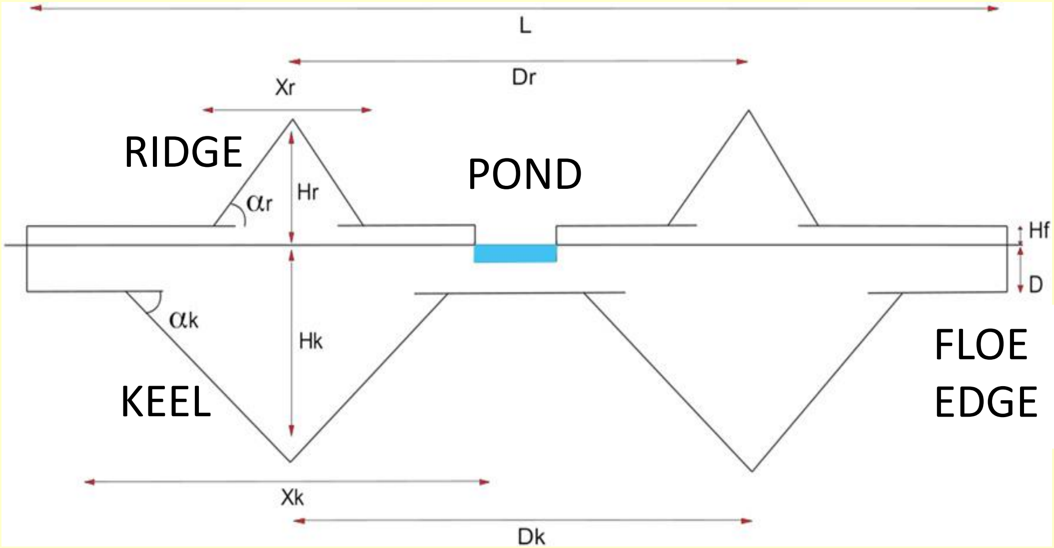
- Scaling analysis of Navier-Stokes equations demonstrates that air and ocean drag laws must be of the form

$$\tau = \rho C_D U^2$$

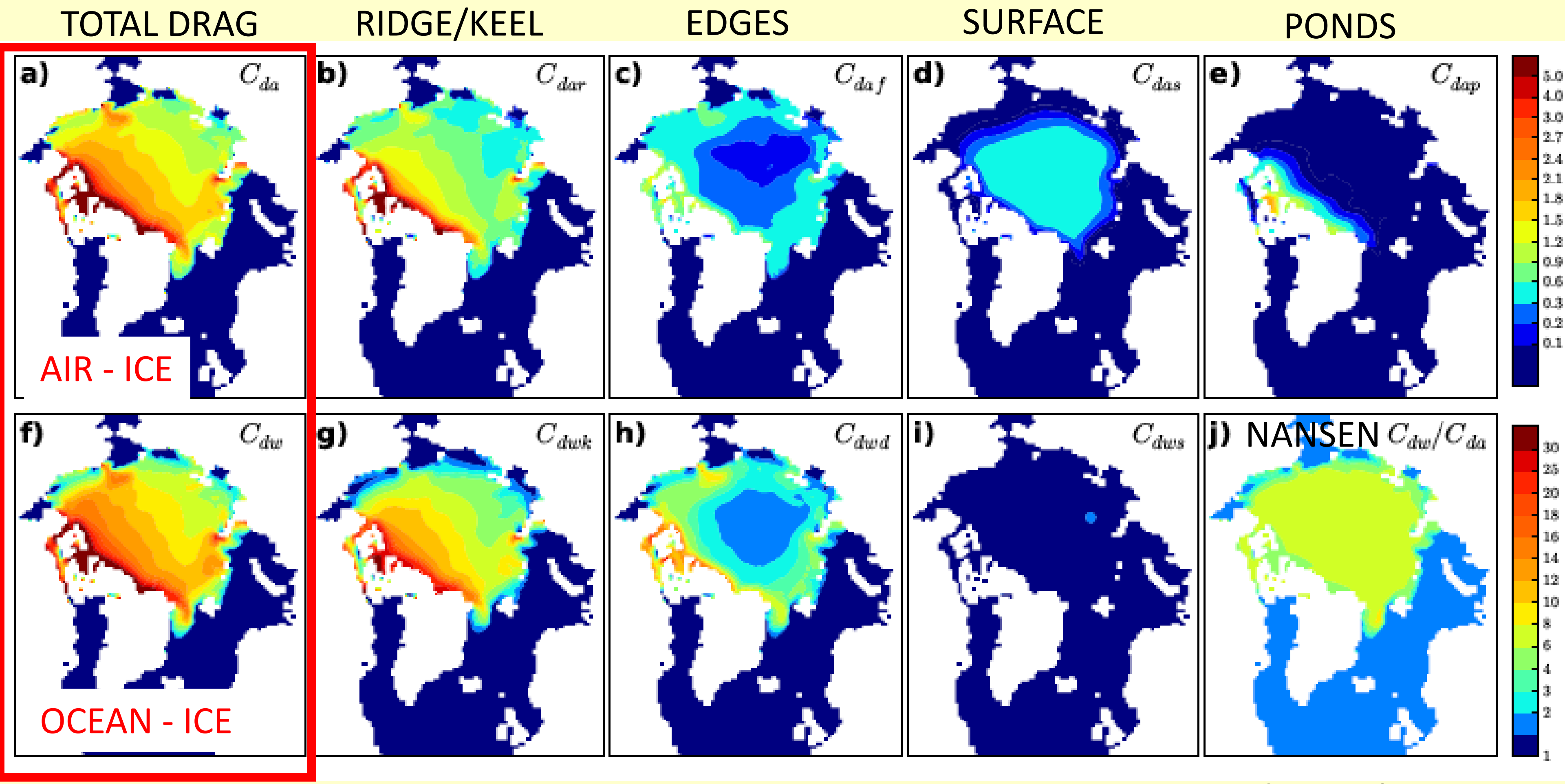
where C_D is the drag coefficient.



- This drag law accounts for both **skin drag** and **form drag**, which depends on **topography** but climate models use a constant drag coefficient C_D.
- We [Tsamados et al, 2014] developed a model that **calculates** the skin and form drag contributions to the drag coefficients at the air-ice and ice-ocean interfaces using a semi-empirical geometry.



Map of drag coefficients, average September 1990-2007



Tsamados et al, 2014

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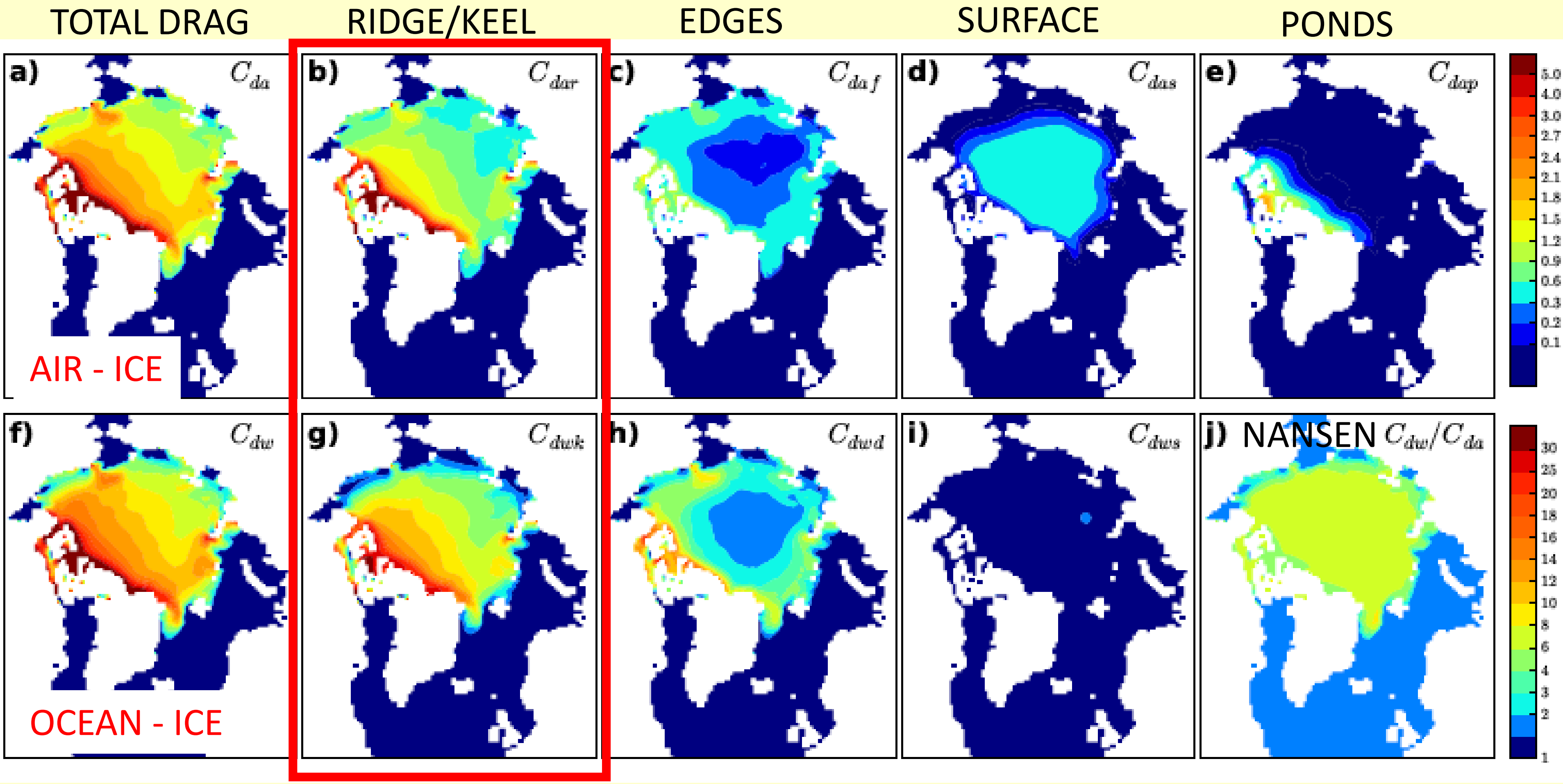

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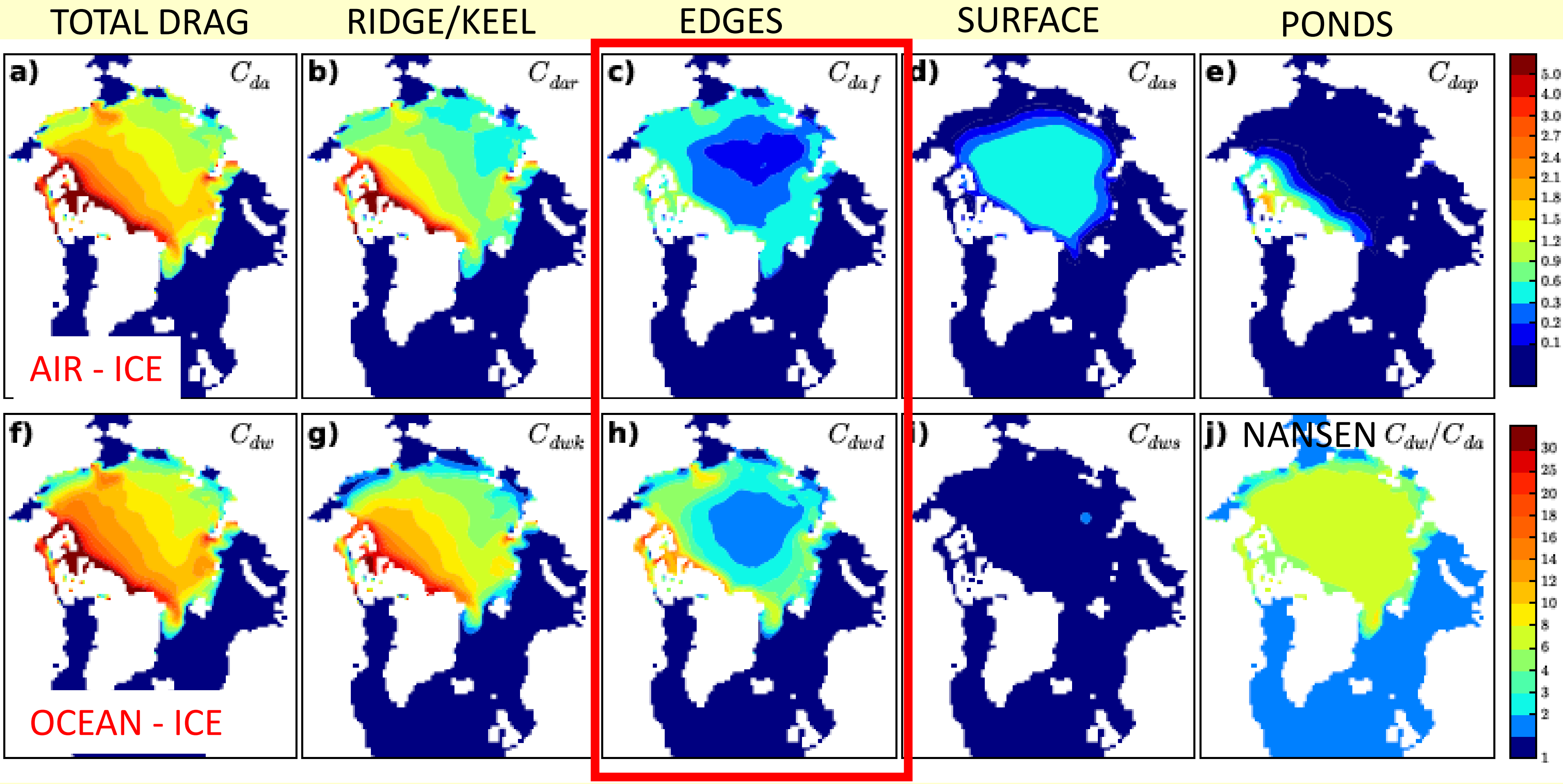
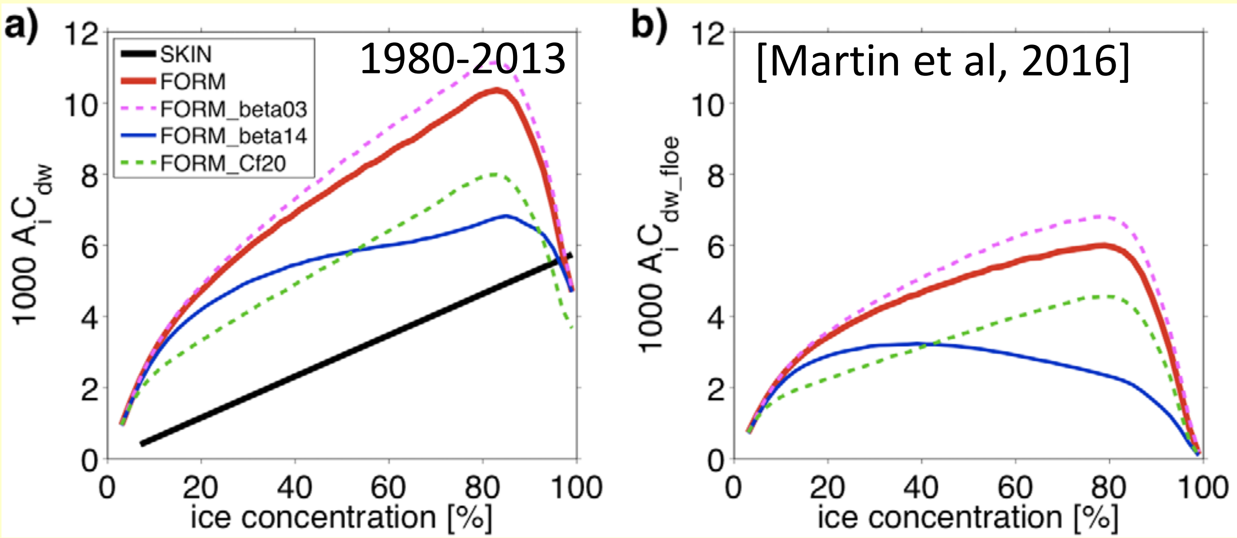


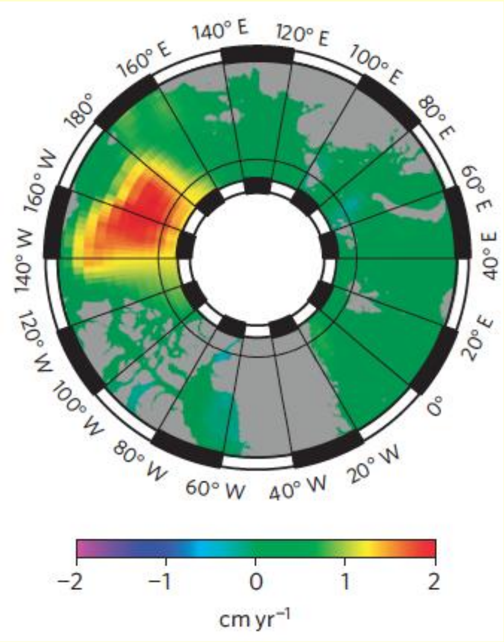
Tsamados et al, 2014

- Spatial variation of total drag coefficient of a factor of 4
- Ridge/keel form drag dominates.. but floe edge drag is significant

Form drag in the coming decades

- Impact of new drag physics on the ice state is **significant**, and introduces **additional spatial and temporal variability** into sea ice simulations.
- This is ongoing work, e.g. recently included **internal wave-induced drag** caused by keels dragging through the ocean mixed layer [Flocco et al, subm.].





[Giles et al, 2012]

- **Floe edge drag** results in a maximum of ice-ocean drag coefficient at ice concentrations *A*~0.8, i.e. similar to what we can expect in the coming decades.

➢ Impact on **spin up/spin down** of the Arctic Ocean.

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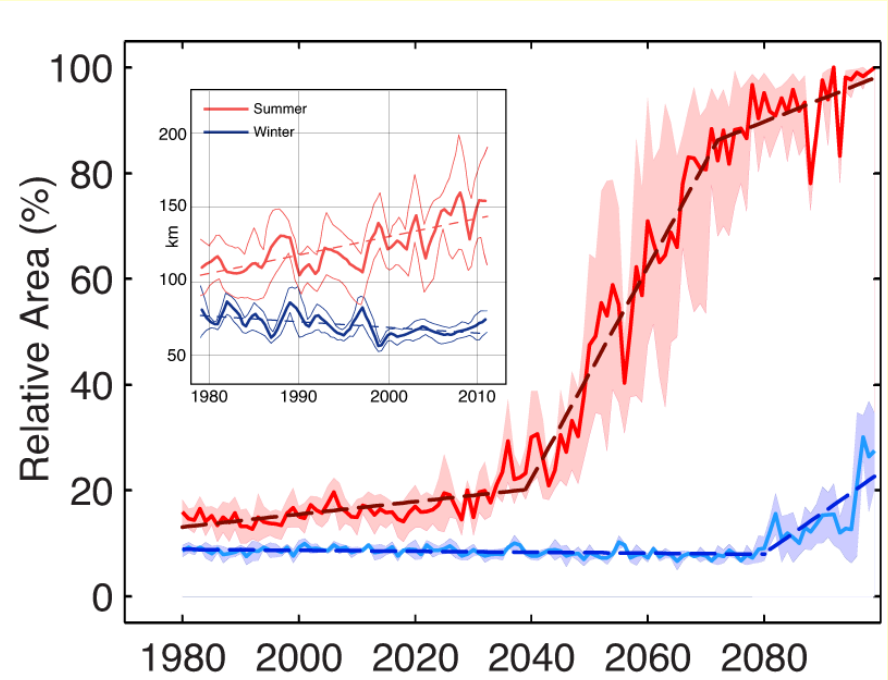
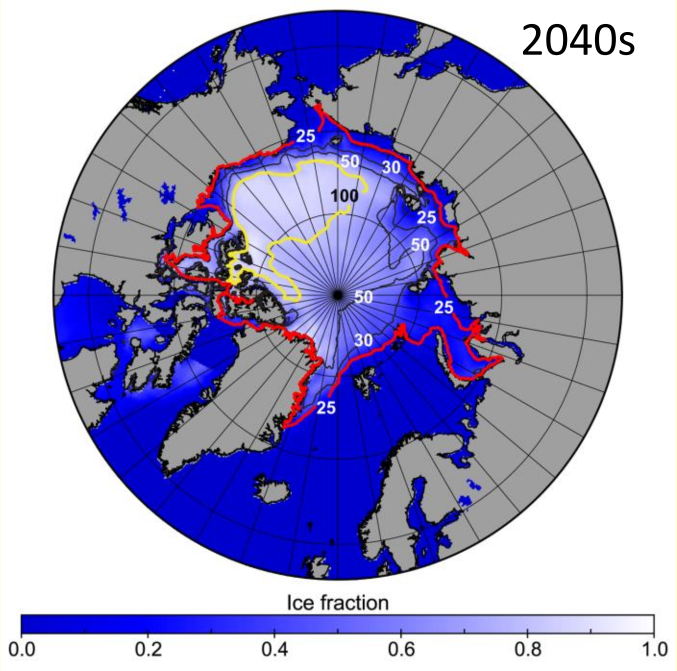
- **Physics of the Marginal Ice Zone** - the region of low ice concentration ($0.15<A<0.8$) is increasing, and this is a region where, *inter alia*, wave-ice interaction, floe collisions, and floe edge drag can become important

An increased marginal ice zone is expected in the coming decades

- Marginal Ice Zone (MIZ) ≡ region with ice area fraction $0.15 < A < 0.8$
- MIZ is ~10% ice area now. This will increase dramatically in the coming decades.





Existing [Strong and Rigor, 2013; inset] and projected changes in the MIZ [Aksenov et al, 2017]

Strengthening feedbacks as ice becomes more marginal

As the MIZ increases, feedbacks expected to strengthen include:

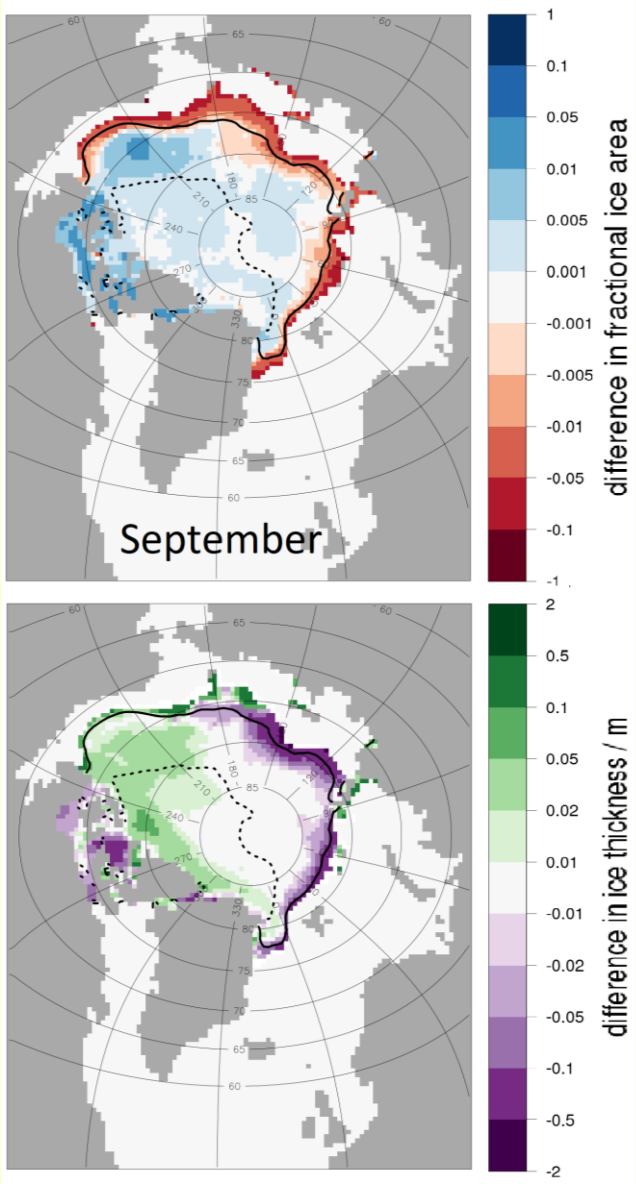
(i) greater ocean wave propagation, more breakup of the ice resulting in a greater total floe edge length, greater lateral melt, and so on;

(ii) greater stirring of the ocean mixed layer (from air drag and floe motion), resulting in enhanced ocean heat transfer to ice floes, resulting in more melt, smaller floes, and so on;

(iii) freshening the mixed layer from greater ice melt, causing it to become shallower, intensifying its warming from solar insolation, resulting in further ice melt, and so on.

These and **many other** feedbacks associated with the deep ocean, atmosphere, and wider climate system will be affected by an increase in extent of marginal ice.

Adequately capturing many of these feedbacks may require the use of a new state variable – the **Floe Size Distribution** (FSD)



Impact of power law FSD on sea ice concentration and thickness in 2007 [Bateson et al, in progress.]

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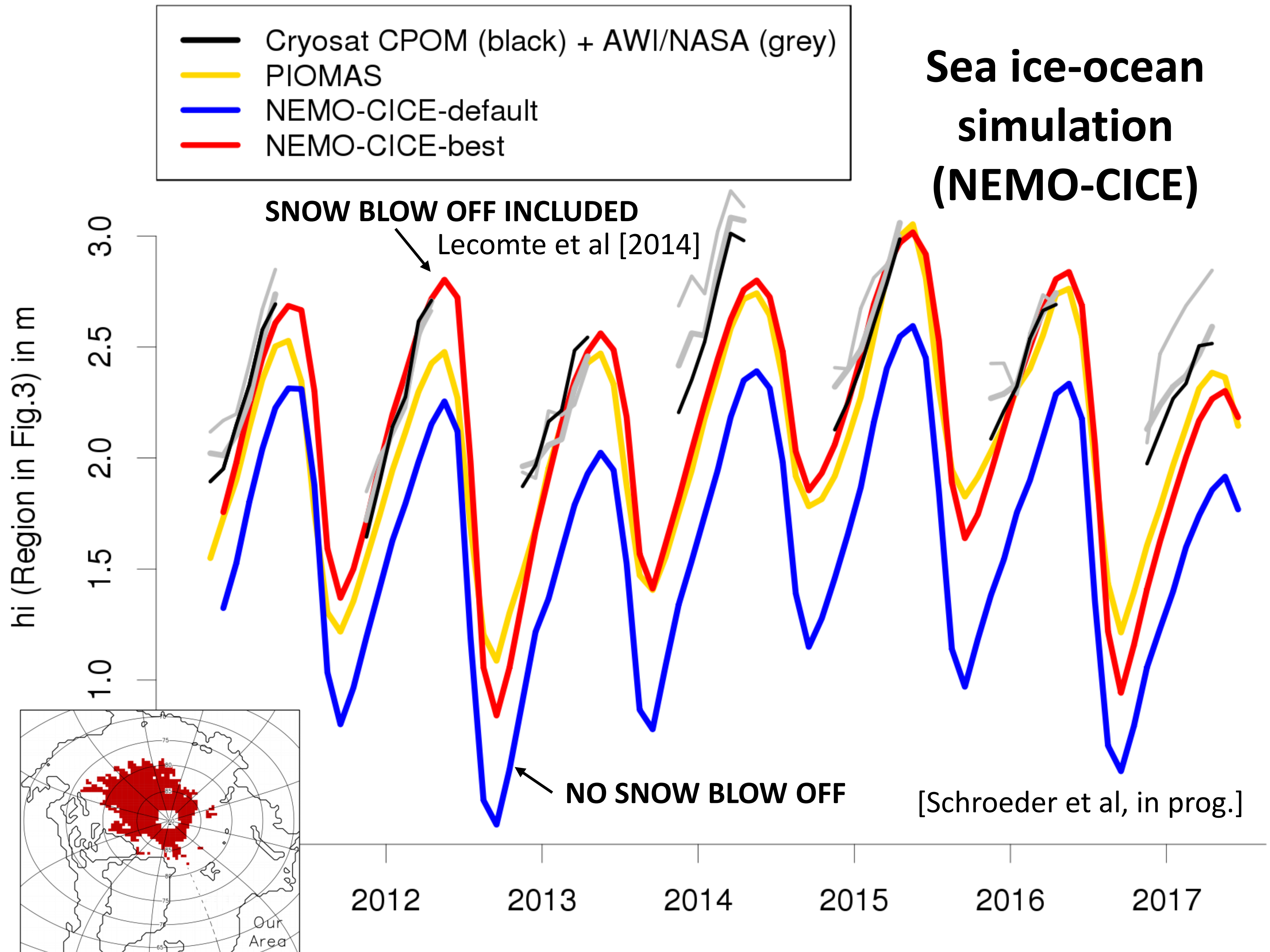

Cryosat CPOM (black) + AWI/NASA (grey)
PIOMAS
NEMO-CICE-default
NEMO-CICE-best
Sea ice-ocean simulation (NEMO-CICE)
SNOW BLOW OFF INCLUDED
Lecomte et al [2014]
NO SNOW BLOW OFF
[Schroeder et al, in prog.]
hi (Region in Fig.3) in m
1.0
1.5
2.0
2.5
3.0
2012
2013
2014
2015
2016
2017
Our Area

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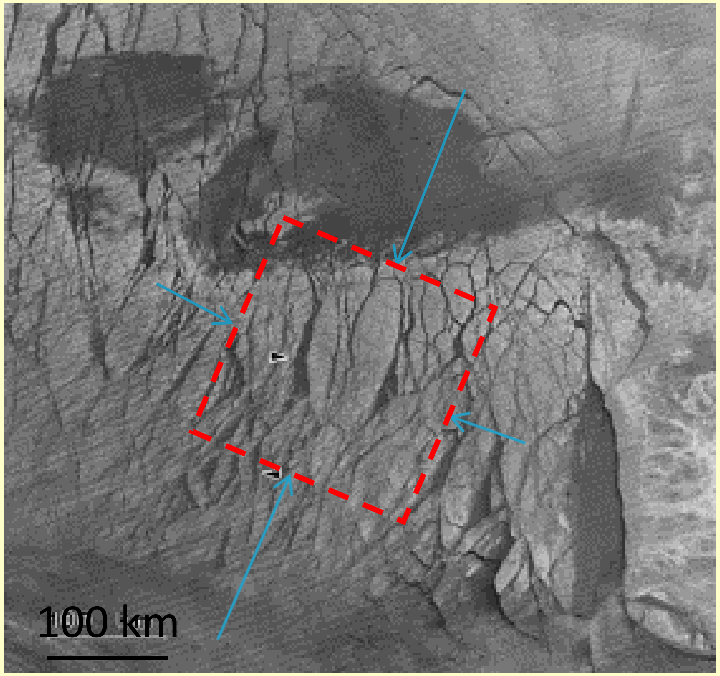
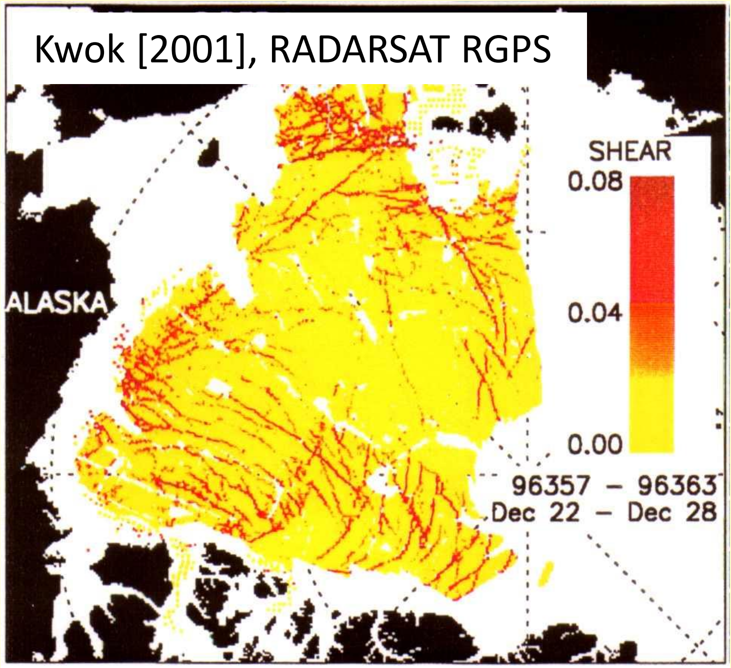
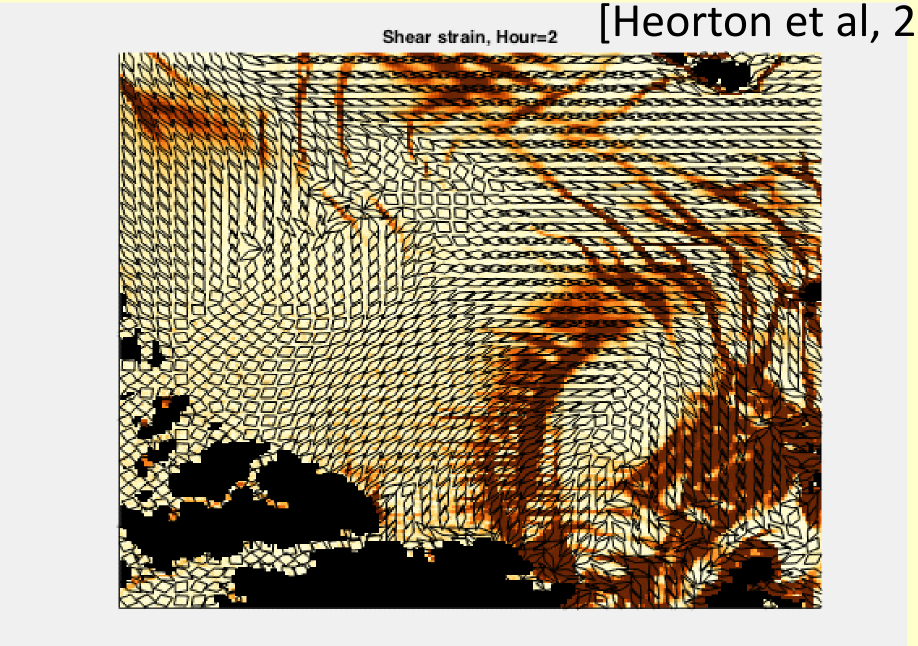
Sea ice rheology: accounting for the observed anisotropy





Linear Kinematic Features

[Heorton et al, 2018]



- Observations show **anisotropy** in the sea ice cover at a wide range of scales
- An **Elastic Anisotropic Plastic** rheology has been developed [Wilchinsky and Feltham, 2006], now included in CICE
- EAP introduces an **anisotropic damage state** (structure tensor), motivated by lab measurement Schulson [2000]
- EAP is computationally efficient and will be future UK climate models

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- **Rheology** - Important now, and poorly represented in most models, but may become less important for **decadal** predictions?
- **Frazil ice formation** and **brine release** - as the seasonal cycle of sea ice area coverage increases, the processes of new ice formation and brine release will create a larger buoyancy forcing to the ocean. Arctic approaching Southern Ocean conditions… ?

The exam questions

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- Synoptic vs *in situ* observations:

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In situ: observations are harder to directly use as a test of climate models. But they give insight into physics, e.g. my melt pond parameterisations were motivated by observations of ponds during SHEBA and off Point Barrow. Somewhat harder for dynamics due to long-range interactions. Future: MOSAiC?

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- Scaling: field observations are made at the sub-grid scale and assumptions must be made when comparing them to a model. In particular continuum models formally deal with averages. Thus statistical tests are more meaningful.
- Completeness/synchronicity: field data is much more useful to modellers if it is in some sense complete. E.g. simultaneous and coincident measurement of every component of the surface energy budget..

How can we integrate observations better with models? What additional observations would help improving models?

- Synoptic vs *in situ* observations:

Synoptic: Gridded metrics such as ice concentration, thickness and motion are essential for testing and calibrating models. Typically satellite data or aggregated field data. Future: melt pond fraction? floe size distribution?, lead fraction?

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- ADDITIONAL OBSERVATIONS (abbreviated wish list): Pond fraction, snow thickness, sea ice thickness, ocean mixed layer properties, topography, …

Concluding remarks

- For sea ice models increased resolution of numerical models helps mostly through improved boundary forcing (air/ocean)
- Climate sea ice model improvement (physical fidelity and quantitative realism) can be produced using new parameterisations
- A strategic approach to model improvement relies on a combination of numerical experiments (“top-down”) and process observations (“bottom-up”)
- Some examples of known unknowns, and recently developed parameterisations, were given
- Inclusion of suitable parameterisations into the next generation of climate models **may make them more useful** to the study of **decadal variability**, among many other applications

July 4, 2010: Arctic sea ice and melt ponds in the Chukchi Sea.