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

Danny Feltham
Centre for Polar Observation and Modelling
Department of Meteorology,
University of Reading, UK

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.
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.

[Petty et al, 2012]
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. These balances are mediated through processes:

- **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]
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. These balances are mediated through processes:

- **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).

- **Thermodynamic** processes, which control melting, freezing, and dissolving. Example processes are thermal conduction, brine convection, and solar radiation absorption.

Wettlaufer, Worster, Huppert 1997
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**. These balances are mediated through processes:

- **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).

- **Thermodynamic** processes, which control melting, freezing, and dissolving. Example processes are thermal conduction, brine convection, and solar radiation absorption.

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.
The need for parameterisations

- Models show that inadequate sea ice simulation may be caused by uncertain boundary forcing (air and ocean), by uncertain sea ice model physics, or both.
The need for parameterisations

• Models show that inadequate sea ice simulation may be caused by uncertain boundary forcing (air and ocean), by uncertain sea ice model physics, or both.

• Increasing the resolution of atmosphere and ocean is expected to result in more realistic forcing of sea ice, and so more realistic sea ice simulation.
The need for parameterisations

• Models show that **inadequate** sea ice simulation may be caused by **uncertain boundary forcing** (air and ocean), by **uncertain sea ice model physics**, or both.

• **Increasing the resolution** of atmosphere and ocean is expected to result in more realistic forcing of sea ice, and so **more realistic sea ice simulation**.

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

\[
\frac{\partial u}{\partial t} + u \cdot \nabla u = \frac{\tau_a}{m} + \frac{\tau_w}{m} + \frac{1}{m} \nabla \cdot \sigma - f k \times u - g \nabla h
\]
Vertically-integrated (i.e. horizontal) momentum balance is:

\[ \frac{\partial u}{\partial t} + u \cdot \nabla u = \frac{\tau_a}{m} + \frac{\tau_w}{m} + \frac{1}{m} \nabla \cdot \sigma - f k \times u - g \nabla h \]

~5x10^{-7}  ~5x10^{-5}  ~5x10^{-5}  ~5x10^{-5}  ~5x10^{-6}  ~5x10^{-6}  ms^{-2}
Vertically-integrated (i.e. horizontal) momentum balance is:

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

\[\approx 5 \times 10^{-7} \quad \approx 5 \times 10^{-5} \quad \approx 5 \times 10^{-5} \quad \approx 5 \times 10^{-5} \quad \approx 5 \times 10^{-6} \quad \approx 5 \times 10^{-6} \quad \text{ms}^{-2}\]

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

i.e. no turbulence, no eddies, no internal variability
The need for parameterisations

- Models show that **inadequate** sea ice simulation may be caused by **uncertain boundary forcing** (air and ocean), by **uncertain sea ice model physics**, or both.

- **Increasing the resolution** of atmosphere and ocean is expected to result in more realistic forcing of sea ice, and so **more realistic sea ice simulation**.

- 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...

  ...to do this, we need **realistic parameterisations** (representations of sub-grid scale physics).
How should we design a climate model to obtain better predictions of polar climates on timescales of decades?
How should we design a climate model to obtain better predictions of polar climates on timescales of decades?

A: Higher fidelity and higher resolution atmosphere and ocean models are needed to provide boundary forcing and resolve feedbacks with the sea ice cover.
How should we design a climate model to obtain better predictions of polar climates on timescales of decades?

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,
How should we design a climate model to obtain better predictions of polar climates on timescales of decades?

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.

- Ideally, one will use models of increasing levels of coupling to shed insight.
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.

- Ideally, one will use models of increasing levels of coupling to shed insight.

- 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..]

- While the literature contains **many sensitivity** studies, analysis of (non-radiative) air-sea ice-ocean **feedbacks** is **lacking** [Goosse et al, 2018].
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.

- Ideally, one will use models of increasing levels of coupling to shed insight.

- 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..]

- 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.**
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

- **Form drag** - drag associated with sea ice edges likely to increase as the ice concentration decreases across the Arctic, potentially enhancing the efficiency of momentum transfer from the atmosphere to the ocean, e.g. spin up (or spin down)
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

- Spatial variation of total drag coefficient of a factor of 4

Tsamados et al, 2014
Map of drag coefficients, average September 1990-2007

- Spatial variation of total drag coefficient of a factor of 4
- Ridge/keel form drag dominates.

Tsamados et al, 2014
Map of drag coefficients, average September 1990-2007

- 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.].

- **Floe edge drag** results in a maximum of ice-ocean drag coefficient at ice concentrations $A \sim 0.8$, i.e. similar to what we can expect in the coming decades.
  - Impact on **spin up/spin down** of the Arctic Ocean.
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

- **Form drag** - drag associated with sea ice edges likely to increase as the ice concentration decreases across the Arctic, potentially enhancing the efficiency of momentum transfer from the atmosphere to the ocean, e.g. spin up (or spin down)

- **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) $\equiv$ region with ice area fraction $0.15 < A < 0.8$
- MIZ is $\sim$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.]
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

- **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

- **Form drag** - drag associated with sea ice edges likely to increase as the ice concentration decreases across the Arctic, potentially enhancing the efficiency of momentum transfer from the atmosphere to the ocean, e.g. spin up (or spin down)

- **Snow redistribution/blow off** - not necessarily going to become more important but is a missing process that is hugely significant now
Sea ice-ocean simulation (NEMO-CICE)

Cryosat CPOM (black) + AWI/NASA (grey)
PIOMAS
NEMO-CICE-default
NEMO-CICE-best

SLOW BLOW OFF INCLUDED
Lecomte et al [2014]

[Schroeder et al, in prog.]
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

- **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

- **Form drag** - drag associated with sea ice edges likely to increase as the ice concentration decreases across the Arctic, potentially enhancing the efficiency of momentum transfer from the atmosphere to the ocean, e.g. spin up (or spin down)

- **Snow redistribution/blow off** - not necessarily going to become more important but is a missing process that is hugely significant now

- **Rheology** - Important now, and poorly represented in most models, but may become less important for **decadal** predictions?
• 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
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
- **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
- **Form drag** - drag associated with sea ice edges likely to increase as the ice concentration decreases across the Arctic, potentially enhancing the efficiency of momentum transfer from the atmosphere to the ocean, e.g. spin up (or spin down)
- **Snow redistribution/blow off** - not necessarily going to become more important but is a missing process that is hugely significant now
- **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

• 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?
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?

  *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?
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?

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?

• 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?

  *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?

• **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..

• **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.

Questions?