An Introduction to SI^3

(the Sea Ice modelling Integrated Initiative)

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and the NEMO Sea Ice Working Group

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Overall objective

- The NEMO reference sea ice model has changed since 2020
- 4 sea ice models used to be supported
- SI^3 is now the sole sea ice component in NEMO

- Why this change?
- What is this *new* sea ice model?
- What are its capabilities?

Outline

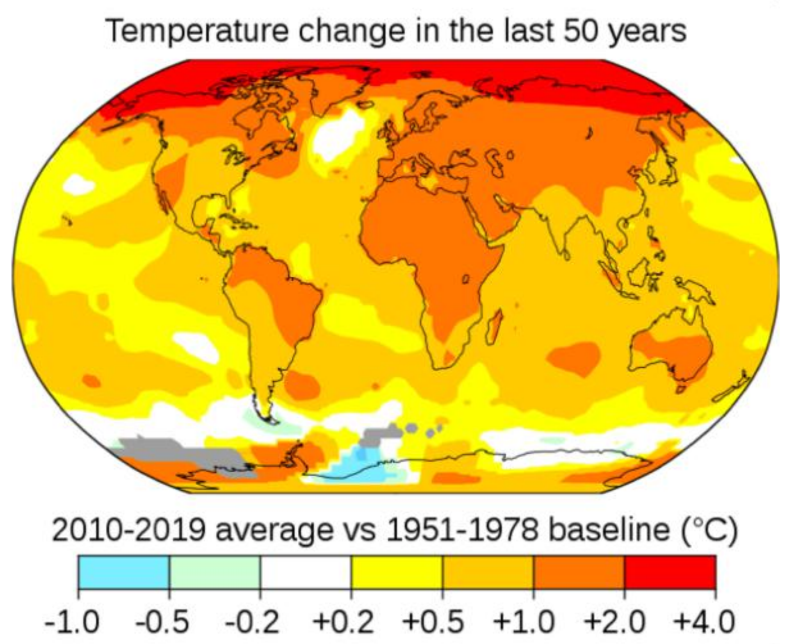
- **Motivation**
- SI3
- Upcoming
- Questionstorm

Sea ice

- Frozen seawater
- Affects ocean and atmosphere
- Biome
- Affects human activities

ESMs need sea ice, an important climate actor and change indicator

- Surface energy balance
- Salt/freshwater uptake/release
- Rapid sea ice changes
- Polar amplification



Representing sea ice in ESMs: historical milestones

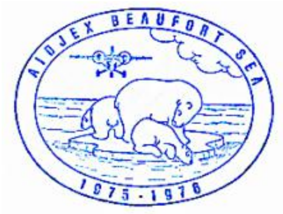
Manabe & Bryan, among the first climate modellers figured they needed sea ice and had it very simple (ice thermodynamics and albedo).

Useful to learn that sea ice matters, but overly simple and abandoned in ESMs early on.

AIDJEX group (1970's) conceptualized a more elaborated sea ice model (thermodynamics, optics, dynamics, subgrid-scale processes, ...)

Mostly standard since IPCC AR3 (2007).

Frank Bryan, Suki Manabe and Joseph Smagorinsky, pioneers of climate modelling at MIT in 1969



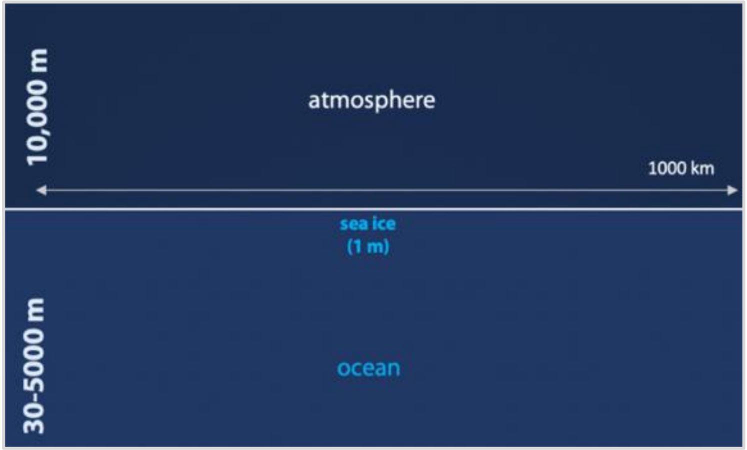
Norbert Untersteiner, lead of the AIDJEX program

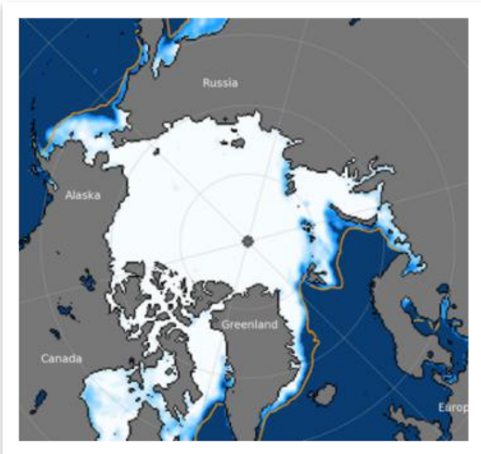
2 key ideas from AIDJEX:
2 + 1D split and continuum assumption

Sea ice is much wider than thin

- Drift is horizontal
- Heat transfer is vertical

- Sea ice is a 2D continuum
- State variables are continuous functions of x,y
- Continuum mechanics laws apply
- Ok if « molecules » (floes) << spatial scales (100km scales)





Passive microwave image of sea ice (25 km scale), giving a sense of continuity

Modelling ingredients for sea ice in ESMs

- All sea ice models for ESM use* follow the **2+1D continuum** approach
- Required features
  - **Horizontal drift** (**2D continuum mechanics** with **non-linear rheology**)
  - **Growth and melt** (**1D thermodynamics**), including **snow**
  - **Open water, optics** (parameterizations)
  - Interactions with **atmosphere and ocean** (parameterizations)
- Optional features: *sensible heat storage, salinity, melt ponds, thickness distribution*
- Significant model differences in terms of **parameterizations** and **numerical implementation**

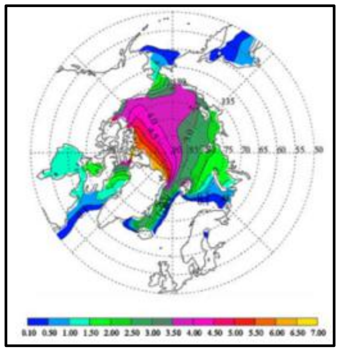
* CICE, SI3, SIS, FESIM, PIOMAS, neXtSIM, ...

Outline

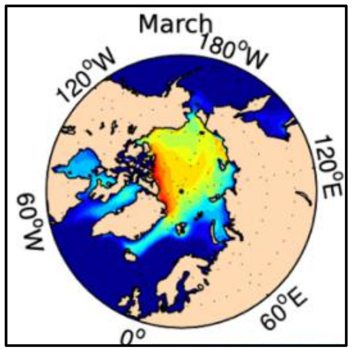
- Motivation
- **SI3**
- Upcoming
- Questionstorm

Sea ice in NEMO

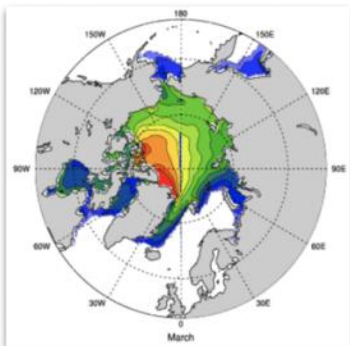
- 1990's: Ice-IF (impose SST=Tf where sea ice is observed)
- 2000's: 4 *continuum* sea ice models (LIM2, LIM3, GELATO, CICE)
- **2010's: Unifying *continuum* sea ice model capabilities into SI^3**
- 2020's: Going further with **SI3**



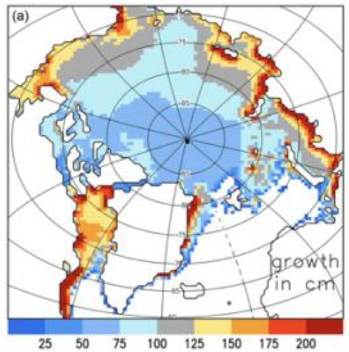
LIM2 (Timmermann et al 2005)



LIM3.6 (Rousset et al. 2015)



GELATO (Salas y Melia, 2002)



CICE (Schröder et al, 2019)

Why unifying NEMO sea ice models?

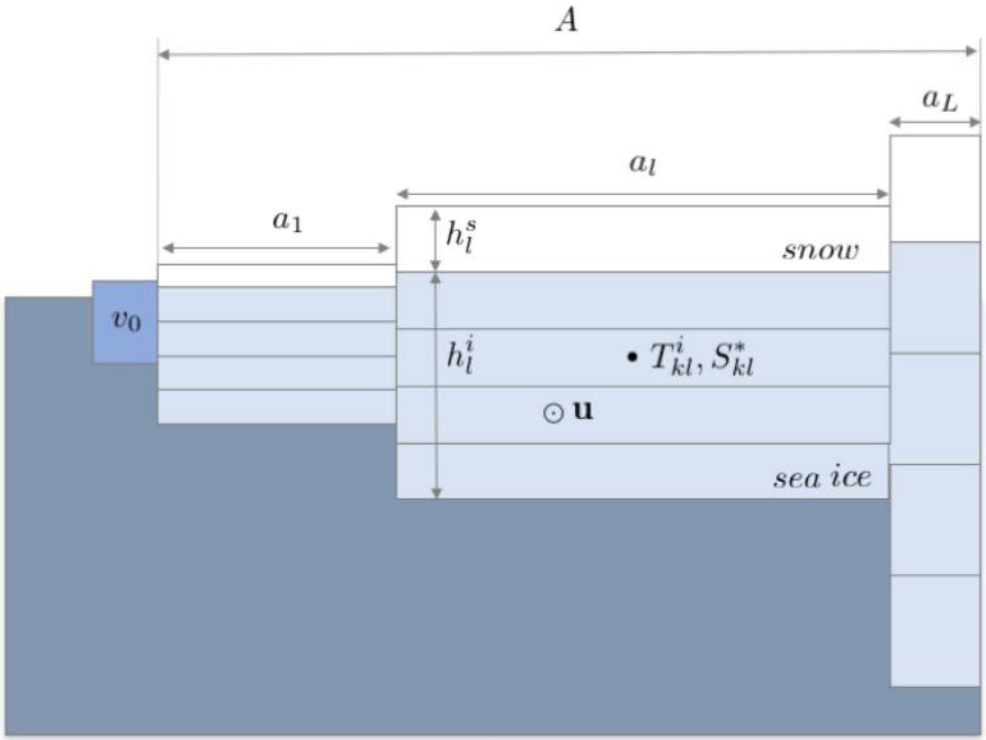
- LIM, CICE and GELATO are essentially the same continuum model
- Maintaining those implies duplication and resource waste
- Unification into SI^3 is best option
  - Reduces duplication
  - Saves resources for scientific progress
  - Brings sea ice fully within the NEMO Consortium (including long-term strategy)

- Unification proposed by NEMO Sea Ice Working Group (**SIWG**)
- **SIWG** gathers sea ice experts from Belgium (UCLouvain), France (CNRS, Mercator, CNRM, IGE), Italy (CMCC), UK (UK MetOffice, UReading, NOC)

Sea Ice modelling Integrated Initiative (SI^3)

- Development coordinated by NEMO SIWG
- Starting from LIM3 (C-grid; NEMO coding/standards)
- Incorporating key functionality from CICE & GELATO
  - Melt-ponds; form-drag; EAP rheology; …
- Met Office/JULES coupling interface
  - Including standard test configuration

SI3 is a 2+1D continuum sea ice model



Conservation of mass, area, energy

$$\frac{\partial X}{\partial t} = -\nabla.(\mathbf{u}X) + \Theta^X + \Psi^X,$$

Conservation of momentum

$$m\frac{\partial \boldsymbol{u}}{\partial t} = \boldsymbol{\nabla} \cdot \boldsymbol{\sigma} + A\left(\boldsymbol{\tau}_a + \boldsymbol{\tau}_w\right) - mf\boldsymbol{k} \times \boldsymbol{u} - mg\boldsymbol{\nabla}\eta$$

Rheology

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}(\dot{\boldsymbol{\epsilon}}, \text{ice state}).$$

Diffusion of heat and surface energy budget

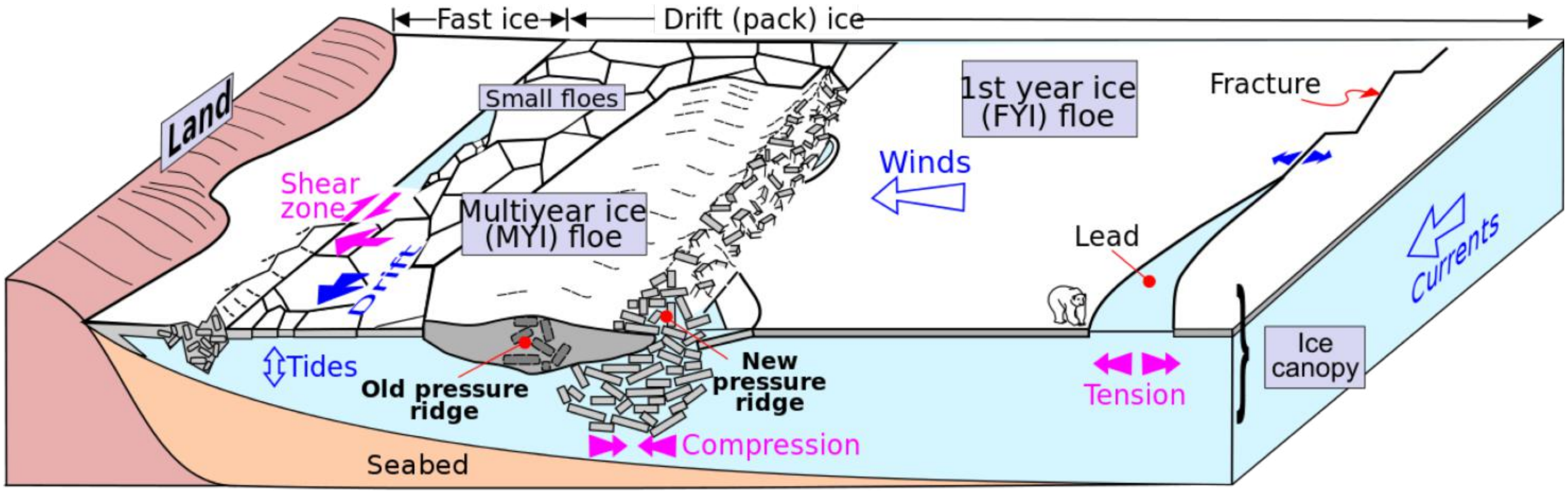
$$\rho\frac{\partial q_m}{\partial t} = -\frac{\partial}{\partial z}(F_c + F_r).$$

$$Q^{sr} + Q^{ns}(T_{su}) = F_c + Q^{sum}.$$

Equation of state

$$q_m(S,T) = \left[c_i(T + \mu S) - L\left(1 + \frac{\mu S}{T}\right) - c_w \mu S\right]$$

Representing sea ice in SI3



approximation:
continuous non-Newtonian fluid

Representing sea ice in SI3

ICE (SI3)

- *dynamics*: drift and deformation
- *thermodynamics*: temperature, salt and thickness changes

Representing sea ice in SI³

ICE (SI3)

dynamics

drift and deformation

thermodynamics

temperature, salt and thickness changes

- Momentum equation

$$m\frac{\partial \mathbf{u}}{\partial t} = \boxed{\nabla \cdot \sigma} + \vec{\tau}_a + \vec{\tau}_w - \hat{k} \times m f \mathbf{u} - mg\nabla H_\circ$$

Internal Stress; Air Drag; Ocean Drag; Coriolis Term; Ocean Surface Tilt

- Thickness distribution equation

$$\frac{\partial g}{\partial t} = -\nabla \cdot (g\mathbf{u}) - \frac{\partial}{\partial h}(fg) + \boxed{\psi}$$

Advection; Thermodynamic growth/melt; Mechanical Redistribution

Ice dynamics in SI3

ICE (SI3)

dynamics

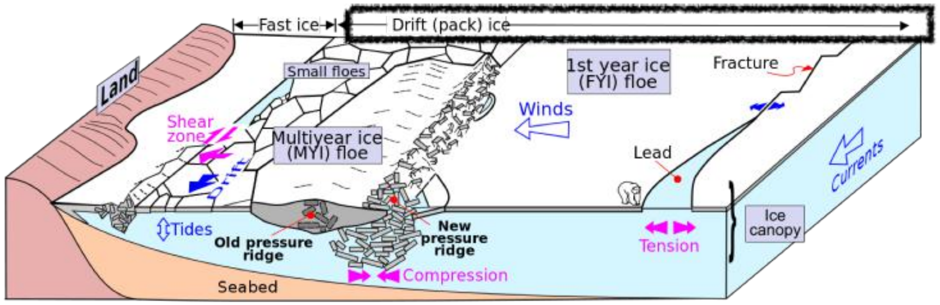
rheology

drift ice

- Momentum equation

$$m\frac{\partial \mathbf{u}}{\partial t} = \nabla \cdot \sigma + \vec{\tau}_a + \vec{\tau}_w - \hat{k} \times m f \mathbf{u} - m g \nabla H_o$$

Internal Stress — Air Drag — Ocean Drag — Coriolis Term — Ocean Surface Tilt



Ice dynamics in SI3

ICE (SI3)

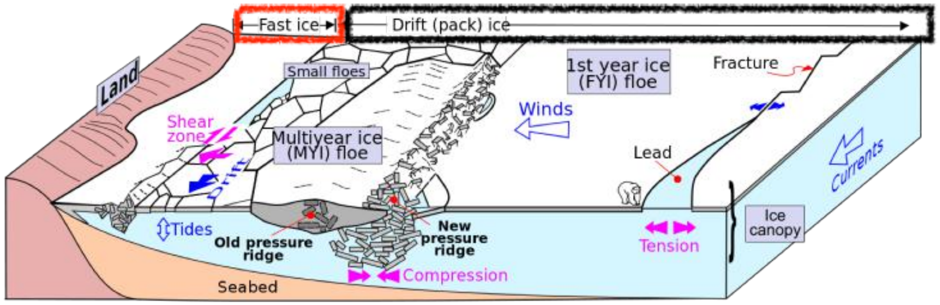
- dynamics
  - rheology

drift ice

- Momentum equation

$$m\frac{\partial \mathbf{u}}{\partial t} = \boxed{\nabla \cdot \sigma} + \vec{\tau}_a + \vec{\tau}_w - \hat{k} \times m f \mathbf{u} - m g \nabla H_\circ$$

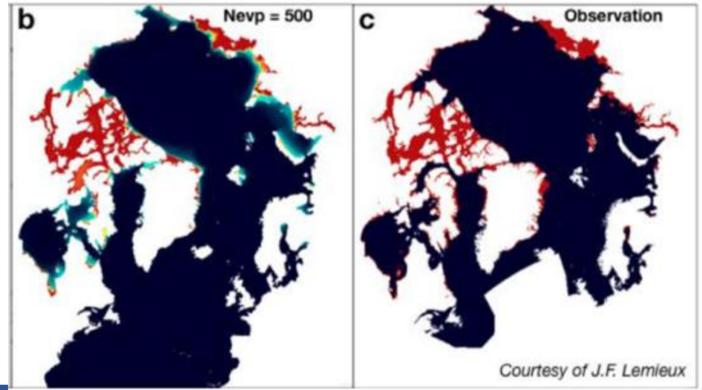
Internal Stress; Air Drag; Ocean Drag; Coriolis Term; Ocean Surface Tilt



landfast ice

$$\tau_{bot} = \sum_{h_i > \Gamma h_{crit}} a_i \tau_{pur}$$

Lemieux et al. (2016)



Ice dynamics in SI³

ICE (SI3)

dynamics

rheology

4 rheologies

Elastic-Viscous-Plastic **EVP**
(Hunke & Dukowicz 1997)

Adaptive Elastic-Viscous-Plastic **aEVP**
(Kimmritz et al. 2016, 2017)

Elastic-Anistropic-Plastic **EAP**
(Tsamados et al. 2013)

Viscous-Plastic **VP**
(Hibler 1979)

2 ice strength formulations

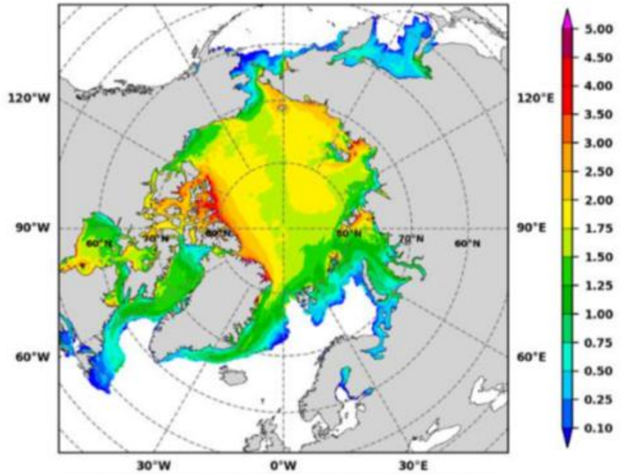
Hibler (1979)

Rothrock (1975)

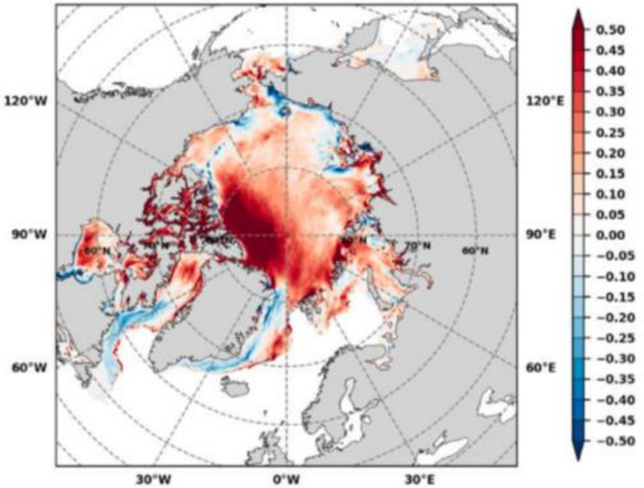
Rheologies in SI^3

Ice thickness (m)

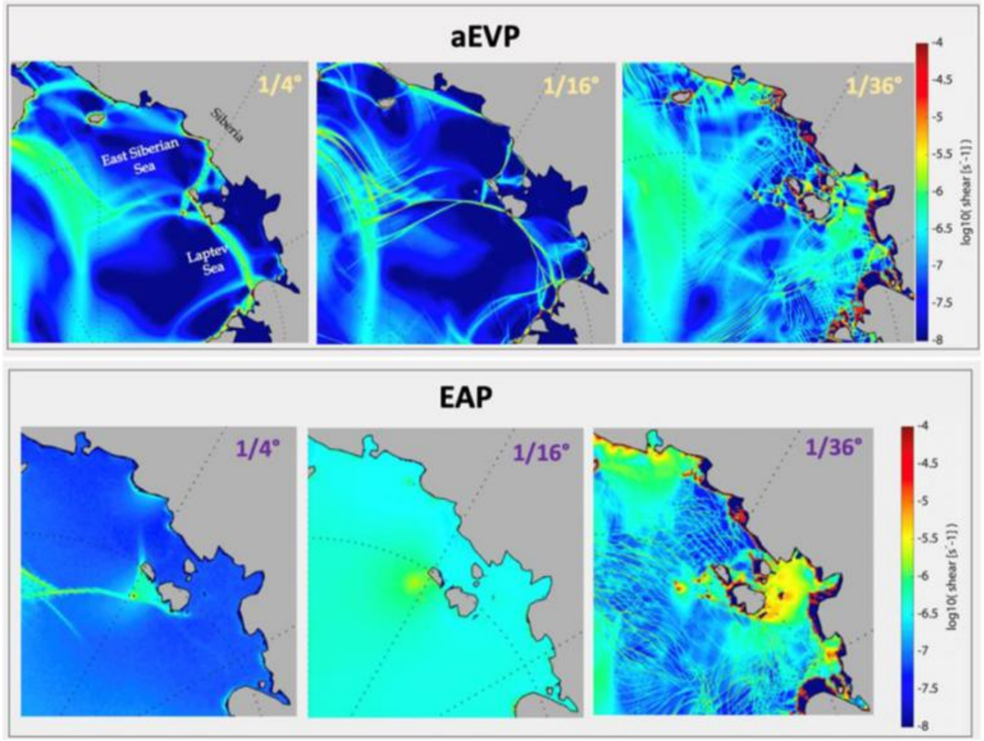
EVP



EAP-EVP



Shear (s-1)



EAP simulates significant different ice thickness wrt EVP

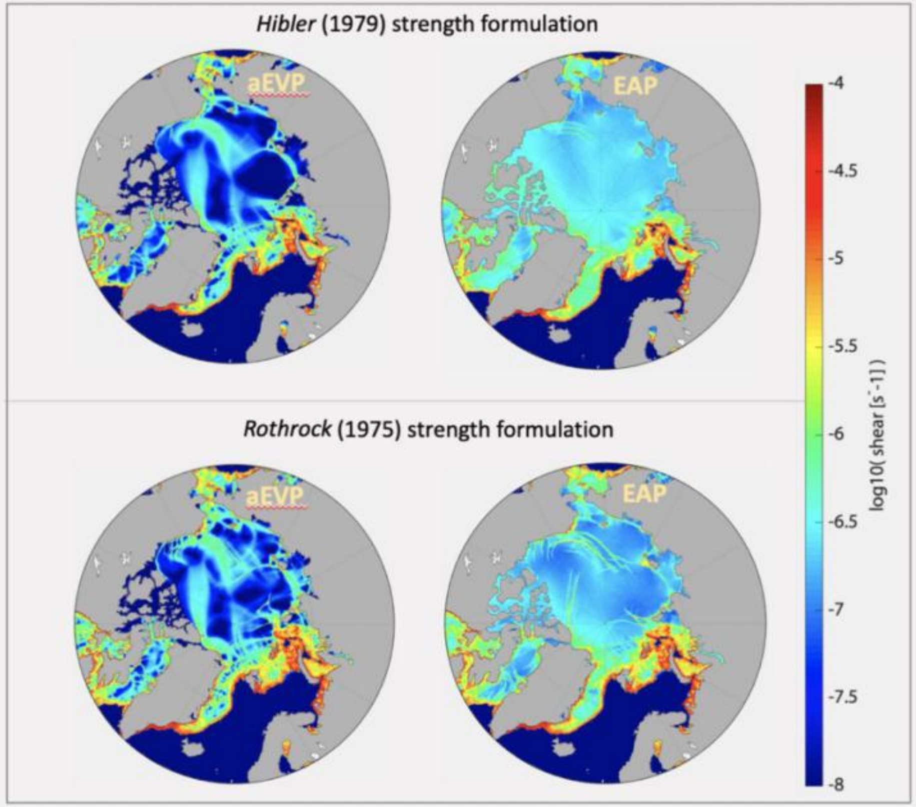
EAP simulates LKFs more accurately at very high resolution

Rheologies in SI³

Shear (s-1)

Hibler (1979)

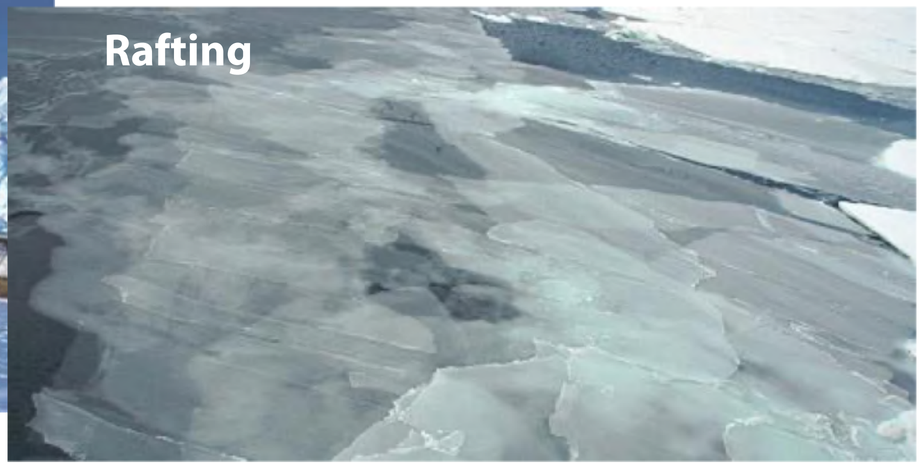
Rothrock (1975)



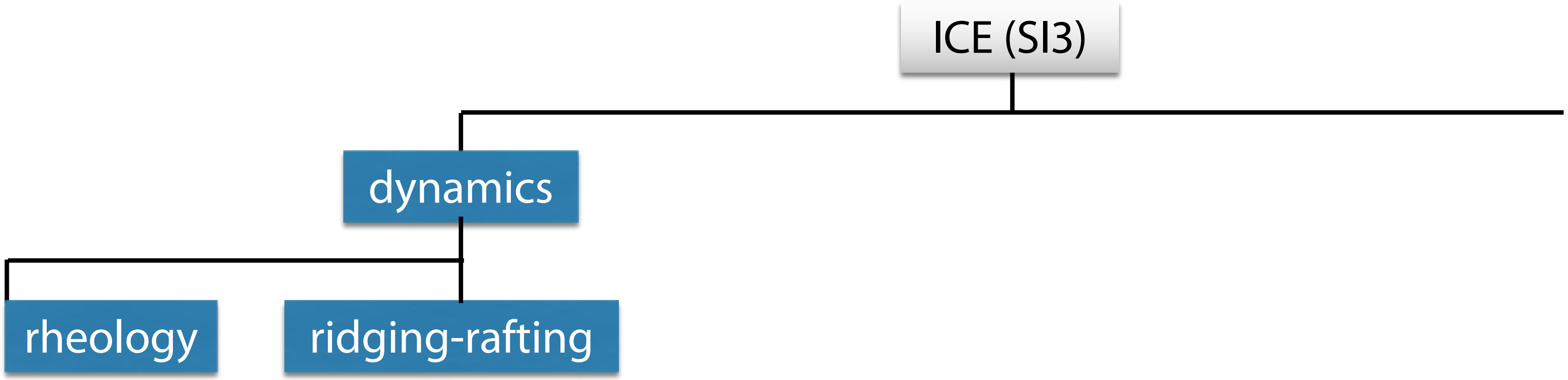
Rothrock scheme increases
the number of small scale fractures

Ice dynamics in SI^3

- ICE (SI3)
  - dynamics
    - rheology
    - ridging-rafting



Ice dynamics in SI³



- Momentum equation

$$m\frac{\partial \mathbf{u}}{\partial t} = \nabla \cdot \sigma + \vec{\tau}_a + \vec{\tau}_w - \hat{k} \times mf\mathbf{u} - mg\nabla H_o$$

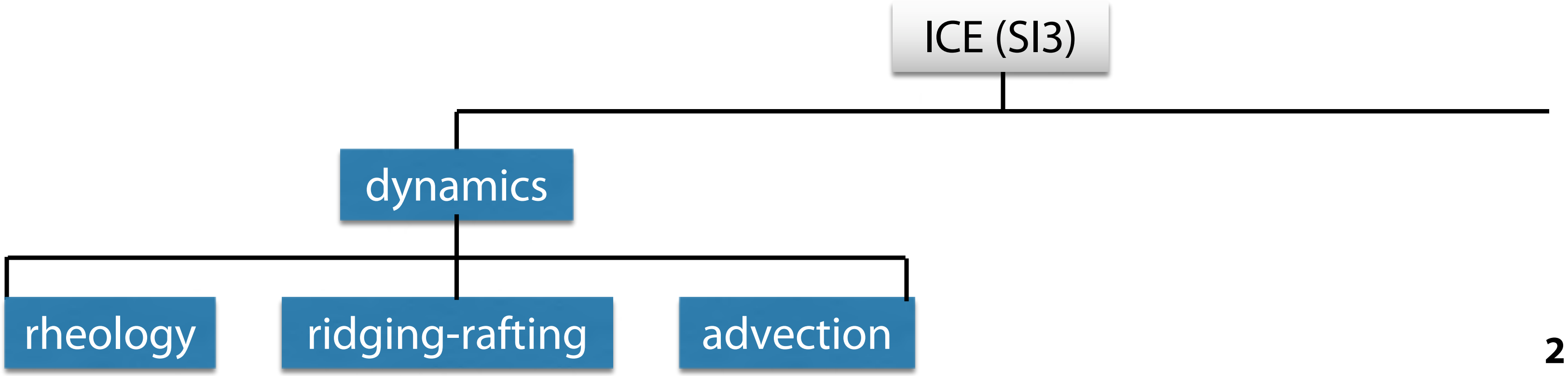
Internal Stress; Air Drag; Ocean Drag; Coriolis Term; Ocean Surface Tilt

- Thickness distribution equation

$$\frac{\partial g}{\partial t} = -\nabla \cdot (g\mathbf{u}) - \frac{\partial}{\partial h}(fg) + \psi$$

Advection; Thermodynamic growth/melt; Mechanical Redistribution

Ice dynamics in SI³



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Internal Stress, Air Drag, Ocean Drag, Coriolis Term, Ocean Surface Tilt

- Thickness distribution equation

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Advection, Thermodynamic growth/melt, Mechanical Redistribution

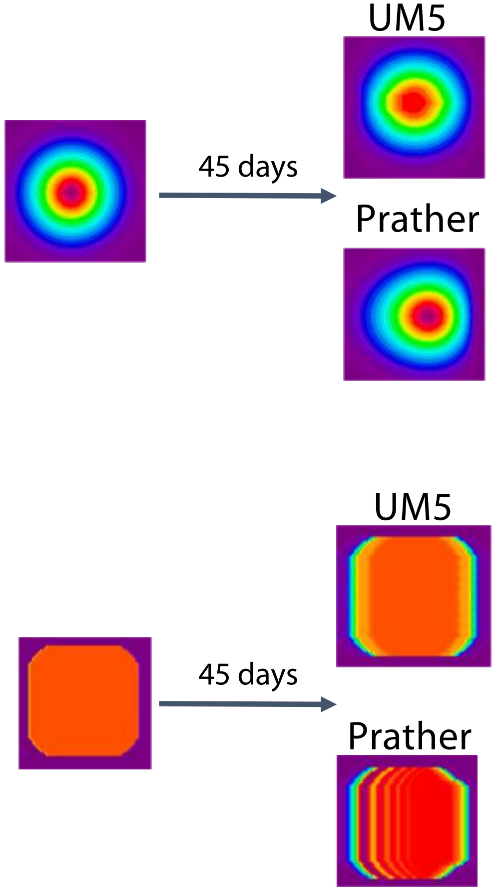
2 schemes

Prather 3rd order
(Prather 1986)

UMx 1-5th order
(Leonard 1991, 1996)

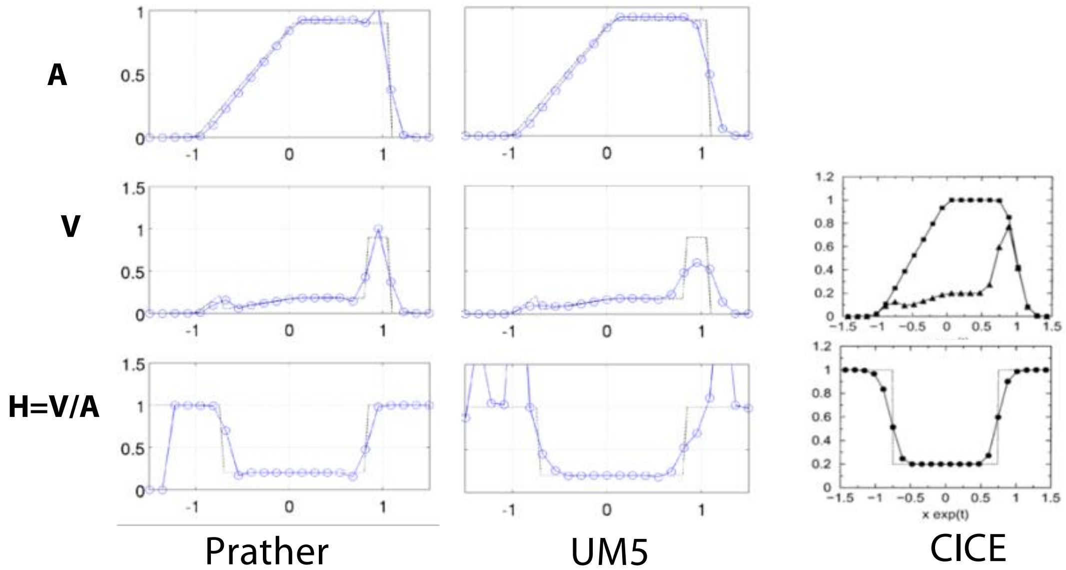
Advection schemes in SI^3

Advection test case



Compatibility test case

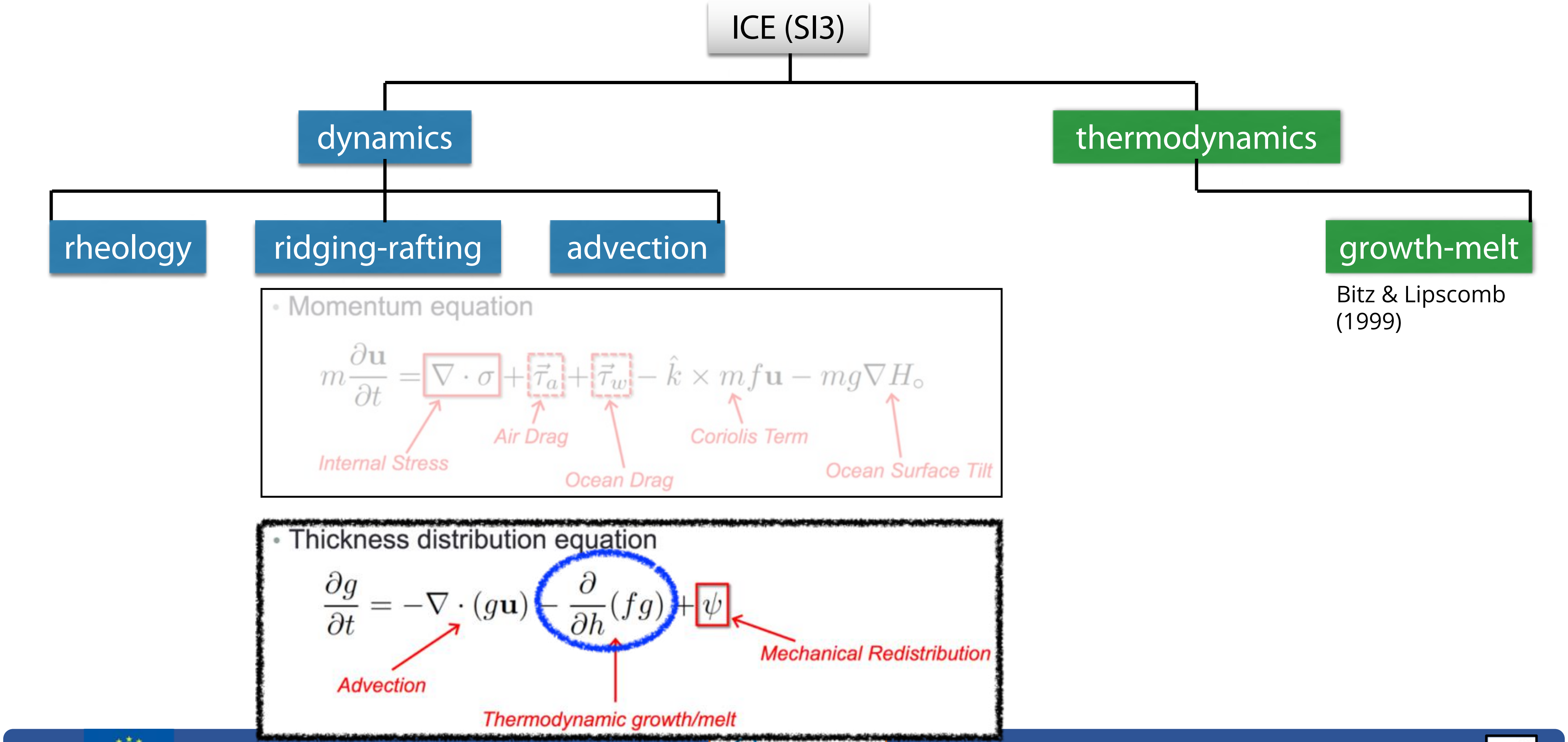
(Schar & Smolarkiewicz 1996)



Prather globally outperforms UMx:

- Better at preserving peaks
- Better at preserving H
- Drawbacks = bad for “step-like” advection

Ice thermodynamics in SI³



Ice thermodynamics in SI^3

ICE (SI3)

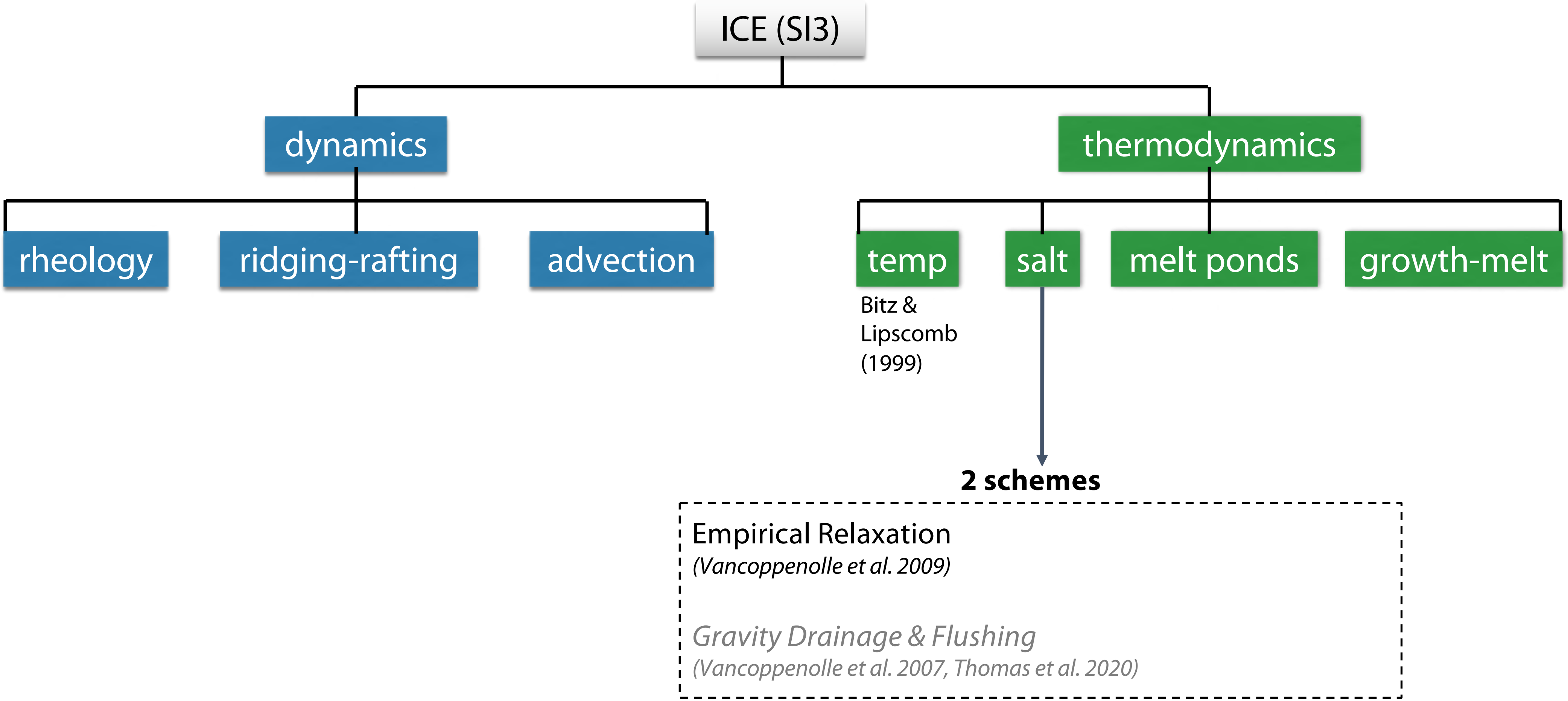
- dynamics
  - rheology
  - ridging-rafting
  - advection
- thermodynamics
  - melt ponds
  - growth-melt

2 schemes

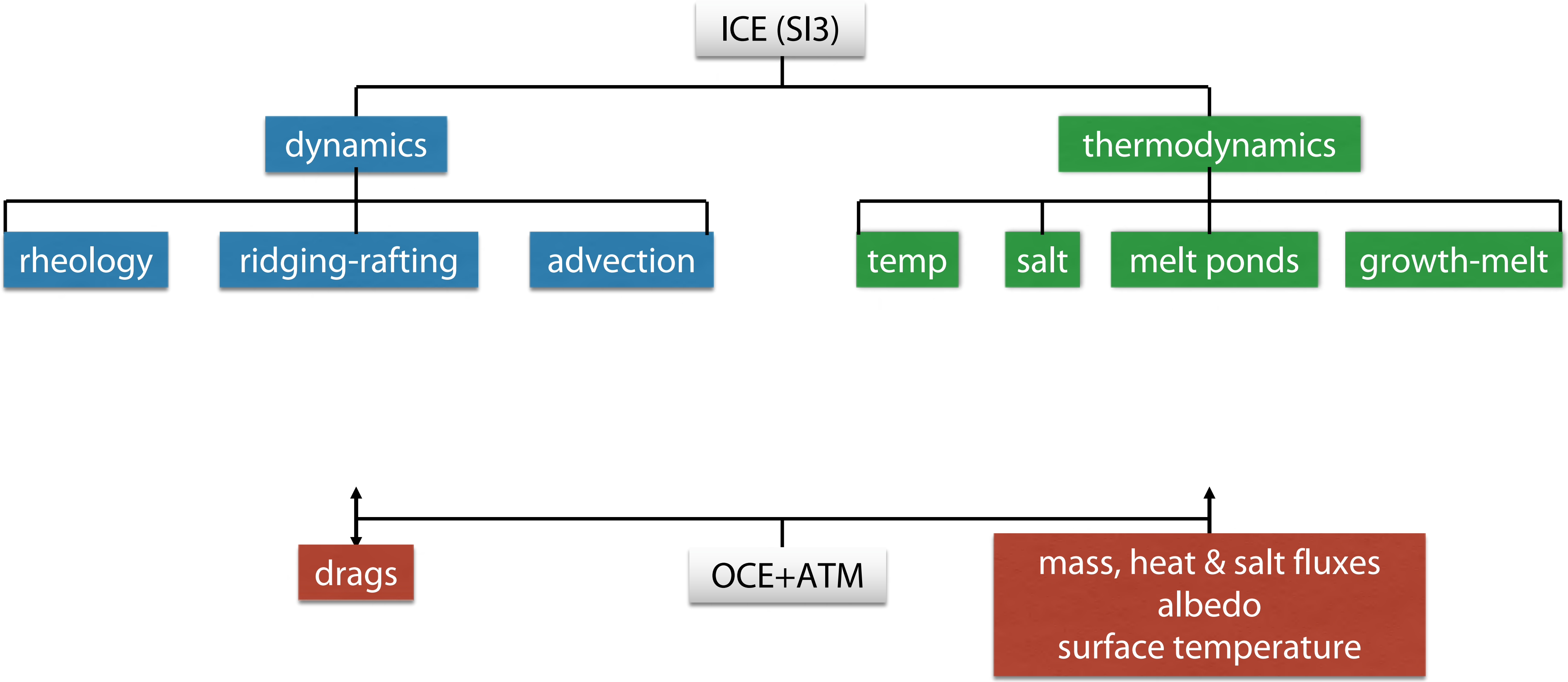
Level ice melt ponds
(Holland et al. 2012, Flocco et al. 2007, 2010, Hunke et al. 2012)

Topographic ice melt ponds
(e.g. Flocco & Feltham 2007)

Ice thermodynamics in SI³

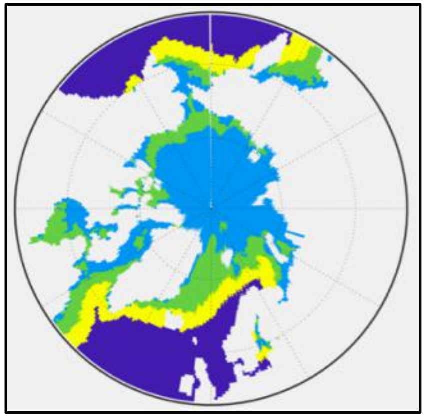


Coupling with ocean+atmosphere



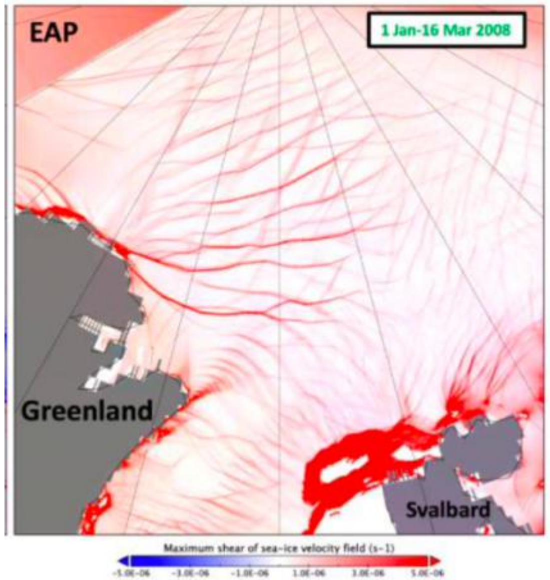
SI^3 benefits from NEMO versatility of use

Global low-res configurations



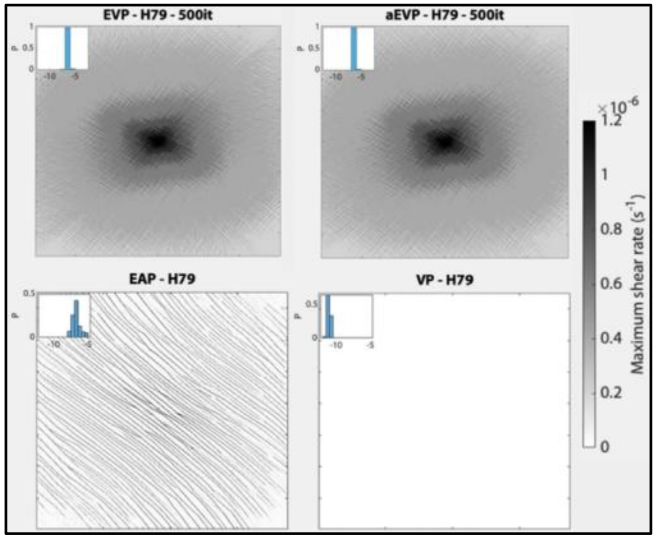
Growth and melt zones in a
1° global configuration
(C. deLavergne)

Regional high-res configurations



Max shear rate in regional 1/36°
Arctic simulations (Rynders and Aksenov)

Idealized test cases



Shear rate in the square-basin
test case of Heorton et al (2017)

Summary of main SI^3 features

	Physics	Description	Ref
Dynamics	Rheology	(a)EVP	Kimmritz et al 2017
		EAP	Wilshinsky and Feltham 2006
		VP	Zhang and Hibler 1997
	Advection	UM5	Leonard, 1991, 1996
		Prather	Prather 1986
Thermodynamics	Mass budget	5-term mass budget	Vancoppenolle et al 2009
	Heat diffusion	Surface-temperature BC	Bitz and Lipscomb 1999
		Conduction-flux BC	West et al 2015
	Salt dynamics	Empirical parameterization	Vancoppenolle et al 2009
	Melt-ponds	Empirical parameterization	Sterlin et al 2021
		Topographic scheme	Flocco and Feltham (2007)
	Albedo	Empirical parameterization	Shine and Henderson-Sellers (1985)

Capabilities and performances

Advantages

- SI3 is "cheap": 25% CPU of a global ice-ocean simulation (10 categories + 10 layers)
- SI3 can be coupled via conductive fluxes
- SI3 is relatively easy to develop
- SI3 can run standalone
- SI3 can be used in global, regional and nested (AGRIF) configurations
- SI3 tuning mainly relies on ice albedos, snow conduction and minimum lead fraction

Drawbacks

- SI3 cannot be used outside of NEMO-ocean framework (ongoing)
- Options not all thoroughly tested:
  - VP / EAP rheologies (cost 5 / 2 times that of EVP)
  - Topographic melt ponds
  - Gravity drainage and Flushing (only for dev)
- Physical improvements developments still needed, missing previously available CICE features

Outline

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- **Upcoming**
- Questionstorm

NEMO Development strategy

- Coordinated long-term strategy plan (2023-2027)
- Chapter 10 for sea ice in NEMO
- Available online
  https://zenodo.org/record/7361464#.ZFn6EewzY-R

10 Sea ice **NEMO Development strategy, 2022**

Lead authors: Martin Vancoppenolle[1]; Ed Blockley[2] and Clément Rousset[1]

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Contributing authors: Aksenov, Yevgeny (NOC, Southampton, UK); Feltham, Danny (CPOM, Reading, UK); Fichefet, Thierry (UCLouvain, Be); Garric, Gilles (MO, Toulouse, Fr); Guemas, Virginie (CNRM, Toulouse, Fr); Holland, Paul (BAS, Cambridge, UK); Iovino, Dorotea (CMCC, Bologna, It); Keeley, Sarah (ECMWF, Reading, UK); Madec, Gurvan (CNRS, Parsi, Fr); Massonnet, François (UCLouvain, Be); Rampal, Pierre (CNRS, Grenoble, Fr); Ridley, Jeff (Met Office, Exeter, UK); Schroeder, David (CPOM, Reading, UK); Tietsche, Steffen (ECMWF, Bonn, Ge).

Strategy: the sea ice continuum model, challenged but useful

- Overall direction fed by International Workshop on sea ice modelling (Laugarvatn, Iceland, 2019)
- Very high resolutions challenge the continuum model
- Continuum model will remain useful for many years
- Continuum model can be further developed (rheology)
- Need to explore alternatives to continuum model

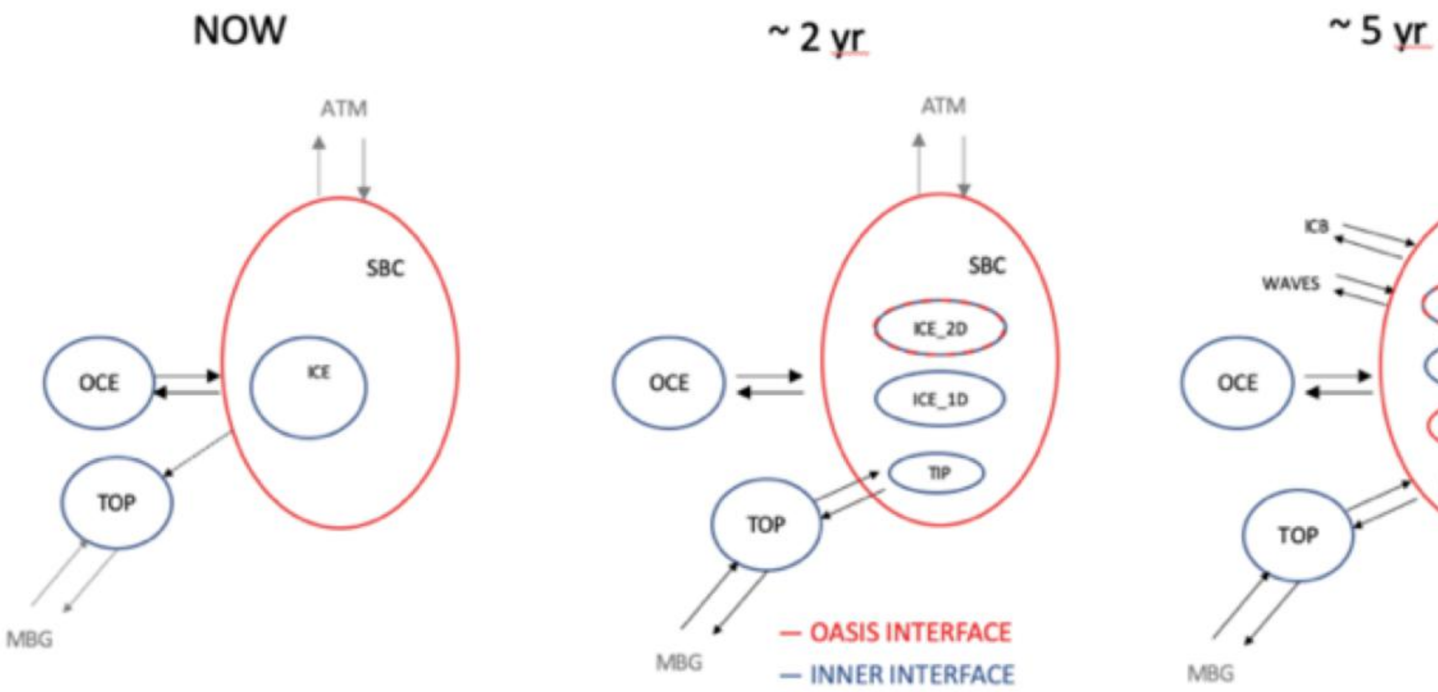
The Future of Sea Ice Modeling
Where Do We Go from Here?

Ed Blockley, Martin Vancoppenolle, Elizabeth Hunke, Cecilia Bitz, Daniel Feltham, Jean-François Lemieux, Martin Losch, Eric Maisonnave, Dirk Notz, Pierre Rampal, Steffen Tietsche, Bruno Tremblay, Adrian Turner, François Massonnet, Einar Ólason, Andrew Roberts, Yevgeny Aksenov, Thierry Fichefet, Gilles Garric, Doroteaciro Iovino, Gurvan Madec, Clément Rousset, David Salas y Melia, and David Schroeder

BAMS (2020)

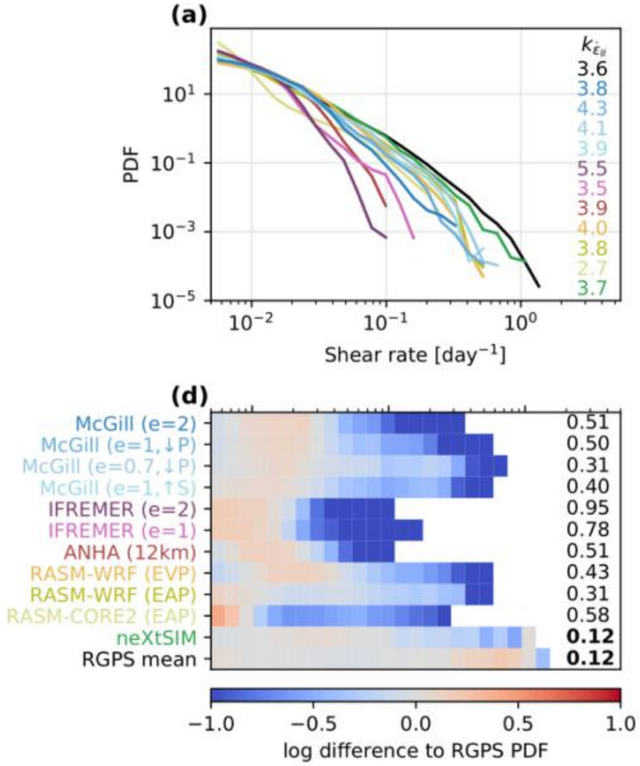
Group picture from Laugarvatn workhop

Strategy highlight: increased modularity



Strategy highlight: ice dynamics

- Pressing questions regarding ice drift & deformation
- *Why some sea ice models better match deformation statistics than others?*
  - *Physics?* **Test new rheologies** (EAP, BBM, …)
  - *Numerics?* **Test alternative numerical implementations of ice dynamics** (SASIP)
  - Needs **more modularity in the dynamic-thermodynamic interface**
- *Is there a spatial scale below which the continuum sea ice model becomes invalid ?*
  - **Explore alternatives** to continuum model (in particular DEMs)

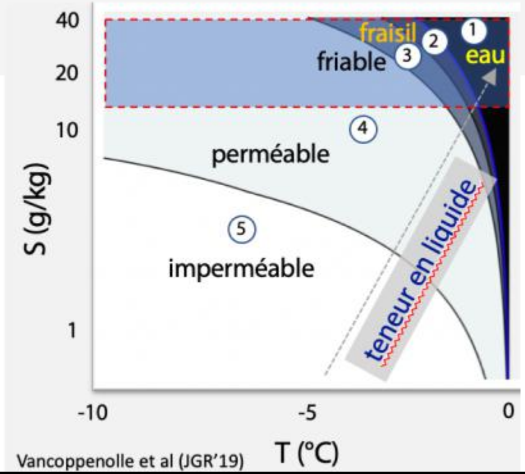


Bouchat et al 2022

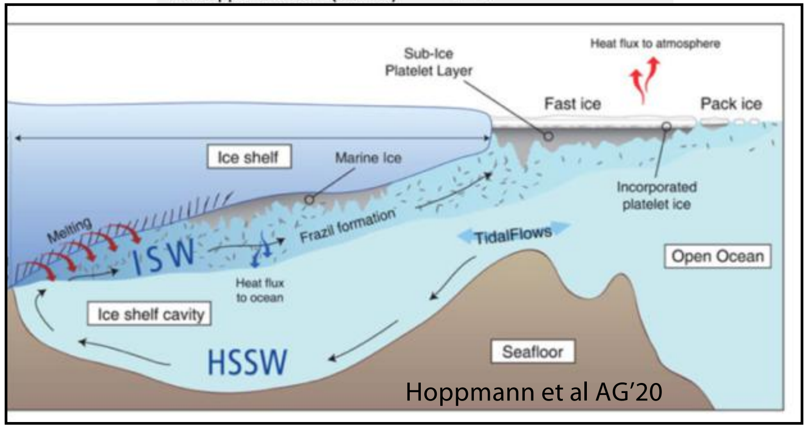
Strategy highlight: more coupling interfaces

- Framework for tracers in sea ice (CNRS) => isotopes, BGC
- Coupling to external snow models (CNRM)
- Coupling to continental cryosphere (UCLouvain, CNRS, IGE)
- Coupling to waves (Ifremer, CNRS, UReading, NOCs)

Strategy highlight: thermodynamics



- Mushy-layer, TEOS-10 compatible thermodynamics
- Improved multi-phase physics (frazil, platelet ice)
- Improved ice optics



Strategy highlight: documentation

- Documentation v1 available since Jan 2023
- Internal review needed
- Paper documenting model capabilities (to be written)

SI3, the NEMO Sea Ice Engine

SI3 doc (2023)

Vancoppenolle, M.; Rousset, C.; Blockley, E.; Aksenov, Y.; Feltham, D.; Fichefet, T.; Garric, G.; Guémas, V.; Iovino, D.; Keeley, S.; Madec, G.; Massonnet, F.; Ridley, Jeff; Schroeder, D.; Tietsche, S.

https://zenodo.org/record/7534900#.ZFn5OuwzY-Q

Outline

- Motivation
- SI3
- Upcoming
- **Questionstorm**

Summary

- SI3 unifies continuum, finite-difference sea ice models previously used in NEMO
- Has increased number of options for physics and coupling with atmosphere
- Follows NEMO standards (physics, numerics, coding style, strategy, ...)

- Many activities presented here were sponsored by IS-ENES3

Questions ?

Further Reading

SI3, the NEMO Sea Ice Engine

SI3 doc (2023)

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The Future of Sea Ice Modeling

Where Do We Go from Here?

BAMS (2020)

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NEMO Development strategy, 2022

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Example questions

- **SI3 contents**
  - Is SI3 better than its predecessors (CICE, LIM, GELATO)?
  - What is new in SI3?
  - What makes SI3 different?
- **Using SI3**
  - How should I get started?
  - Which parameters should I tune?
  - Can I use other sea ice models with NEMO?
  - Can I use SI3 without NEMO?
  - Where asking questions?
- **Developing SI3**
  - How SI3 is evolving? Who decides?
  - Can I contribute to SI3?