# A probabilistic basal stress parameterization

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# Landfast ice

Landfast ice is sea ice that is immobile (or almost immobile) near a coast for a certain period of time.

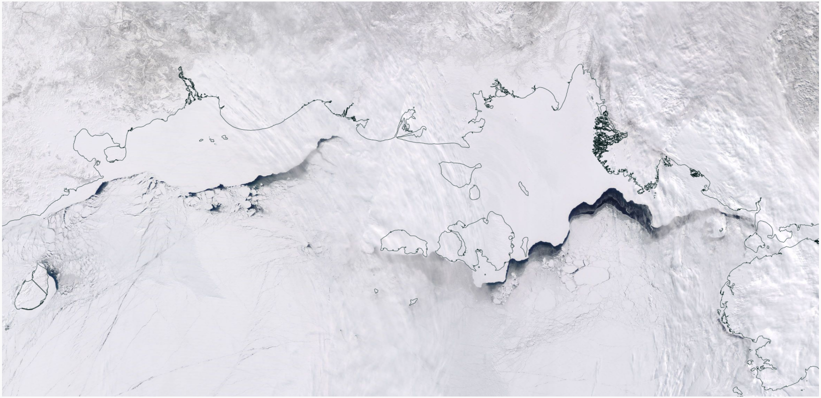


**Figure 1:** MODIS image of the landfast ice cover over the Siberian Shelf on 24 April 2019 (NASA Worldview). The shape of the ice edge indicates the presence of anchored ice capable of resistiung large shear stresses.

# Seabed-ice interaction

Lemieux et al. (2015) introduced a basal stress (seabed-ice friction force) term in the momentum balance equation for sea ice

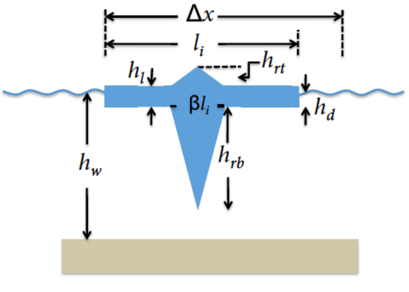
$$\rho_i \frac{D\mathbf{u}}{Dt} = -\rho_i f \hat{\mathbf{k}} \times \mathbf{u} - \rho_i g \nabla \eta + \tau_a + \tau_o + \tau_b + \tau_w + \nabla \cdot \sigma$$

$$\tau_b = \tau_b^{\max} \left( \frac{-\mathbf{u}}{|\mathbf{u}| - u_0} \right) e^{-\alpha_b (1-A)}$$

$\tau_b$ determines **when** sea ice touches the ground and **how strong** is the maximum friction force between the seabed and the ice.

# Seabed-ice interaction

Grounded ice keels produced during compressive ridging events play a role in stabilizing the landfast ice cover. The model of Lemieux et al. (2015) supposes that :




- ridge keels exists at any mean ice thickness.
- ridge keels have a triangular shape (Hibler 1980)
- the keel depth $h_{rb}$ is a linear function of the mean ice thickness $h$

# Seabed-ice interaction

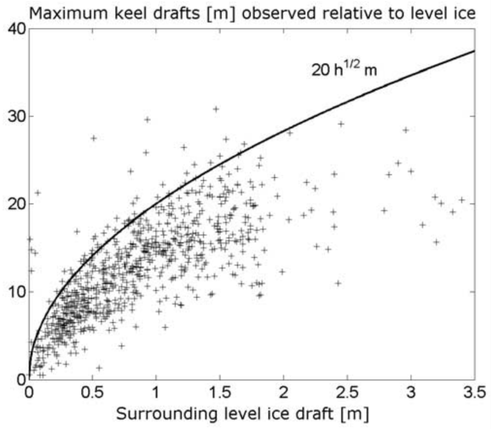


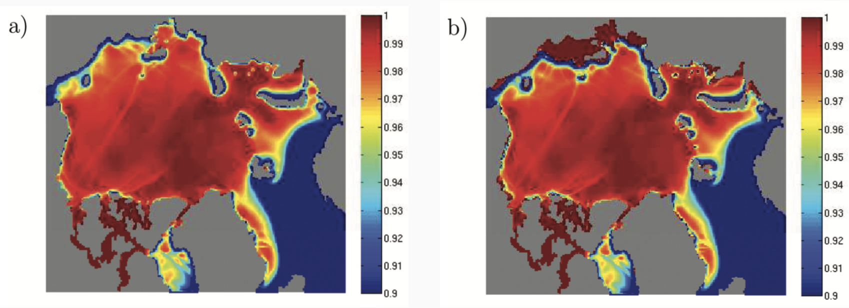

**Figure 2:** Amundrud et al. (2004), Figure 5.

$$\boxed{\tau_b^{\max} = \mu\,(h - h_c)}$$

Based on in situ observations, the keel depth $h_{rb}$ is chosen to be approximately 8 times larger than the surrounding level ice.

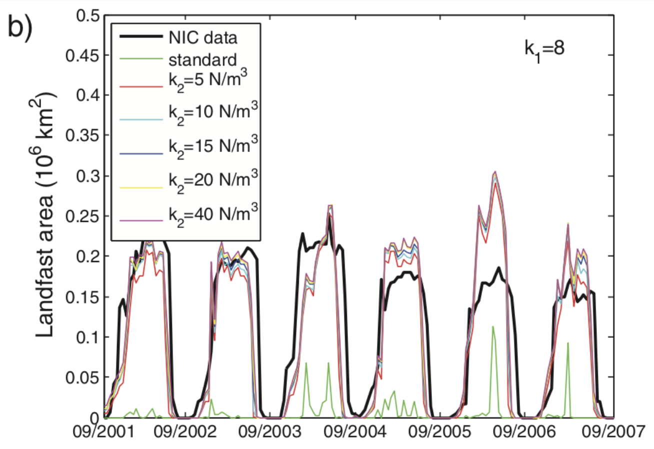
# Main results from Lemieux et al. (2015)

1. Reproduce landfast ice phenology reasonably well.



# Main results from Lemieux et al. (2015)

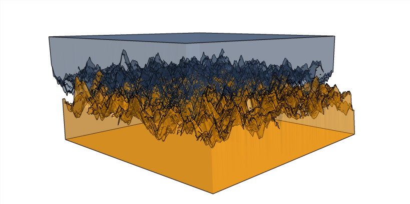
2. Landfast ice phenology not sensitive to the friction coefficient ($k_2$), but highly sensitive to the ridge keel parameterisation ($k_1$).



# Caveats

- Maps a single keel depth value per mean ice thickness, while the mapping is not single-valued.
- Ice thickness distribution (ITD) of ridged sea ice is highly skewed $\rightarrow$ non-linear interactions.
- Tuning with a given dataset over a given period may not be able to predict future trends or new events (non ergodicity).

Recognizing that sea ice models do represent the evolution of the ice thickness distribution and that the bathymetry also has a subgrid scale variability, it makes sense to adopt a probabilistic approach to the problem.



# A probabilistic approach

Let's consider ice thickness and water depth independent random variables $x$ and $y$ following probability density functions $G(x)$ and $B(y)$.

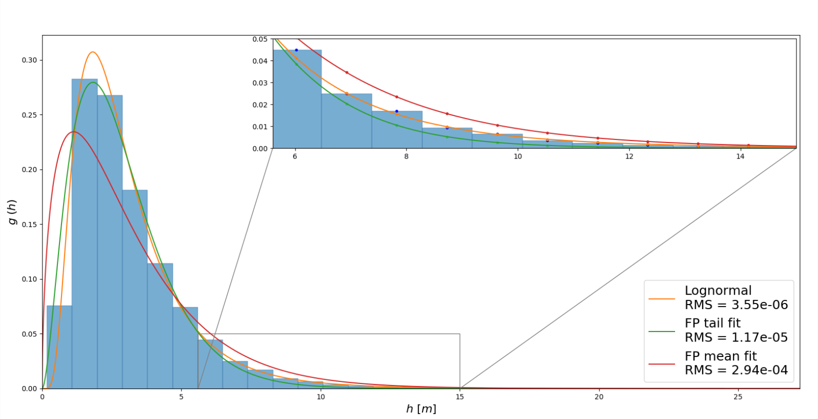
There will be an interaction between the ice and the seabed if the probability that the ice draft $x_d$ is larger than the height of the water column $y$ is non zero. This is obtained as follows :

$$\mathcal{P}(x_d > y) = \int_0^\infty \int_y^\infty G(x_d)\, B(y)\, dx\, dy \tag{1}$$

Assuming isostasy, the total maximum friction stress depends on the normal force exerted by the excess weight of the ice sitting of thickness $x$ on the ocean floor $y$, integrated over all possibilities, given by

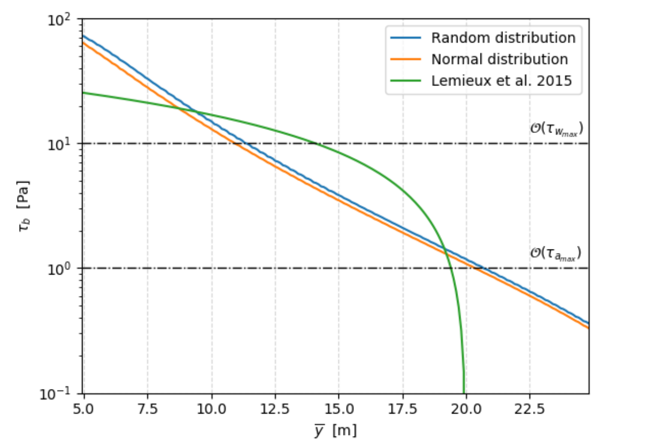
$$\tau_b^{\max} = \int_0^\infty \int_0^x \mu g(\rho_i x - \rho_w y)\; G(x)\; B(y)\; dy\; dx. \tag{2}$$

# A probabilistic approach




For $G(x)$, we choose a log-normal distribution with the same mean $m$ and variance $v$ as the observed ITD represents well the tail of the observed distribution (here data from the NASA Ice Bridge project).

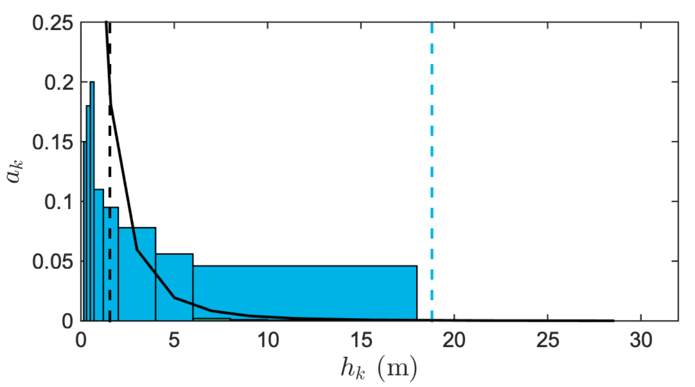
# A probabilistic approach




The probabilistic formulation produces a **non-linear** behaviour that is insensitive to the choice of the bathymetric distribution (here uniform versus normal distributions with same mean and variance).

# Implementation in RIOPS

The Canadian Regional Ice-Ocean Prediction System (RIOPS) uses CICE with 10 thickness categories, with the last category representing ice thicker than 6 m.




The ITD is fitted with a log-normal distribution **truncated at a selected percentile value** $p$, which represents the thickness of the thickest keels.

# Results

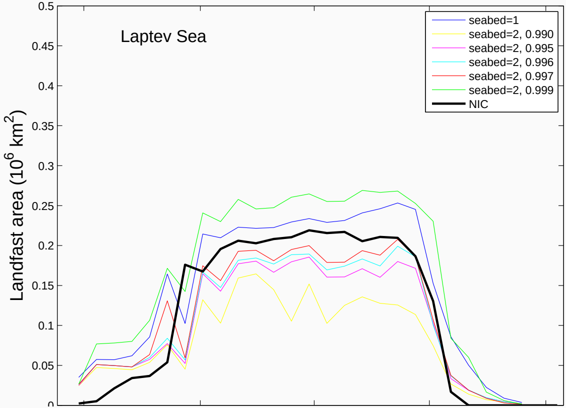



**Figure 3:** Landfast ice extent in the Laptev Sea simulated with the probabilistic approach with different value of *p*, compared with the linear parameterization.

# Results

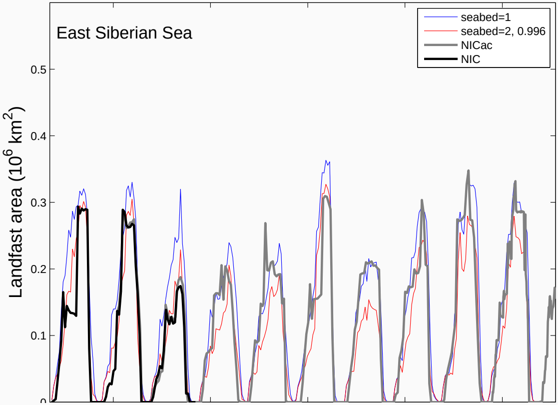



**Figure 4:** Landfast ice extent in the East Siberian Sea as simulated the two models compared with observations (NIC and CMC).

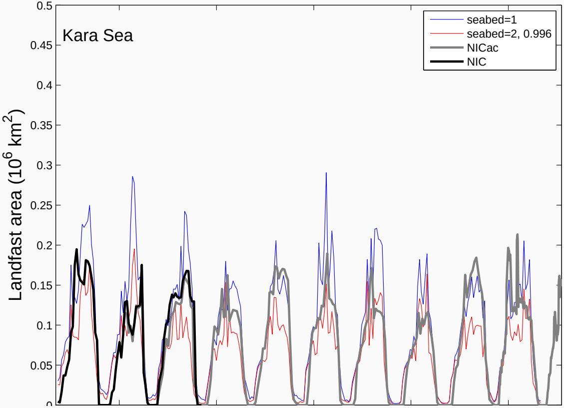



**Figure 5:** Landfast ice extent in the Kara Sea as simulated the two models compared with observations (NIC and CMC).

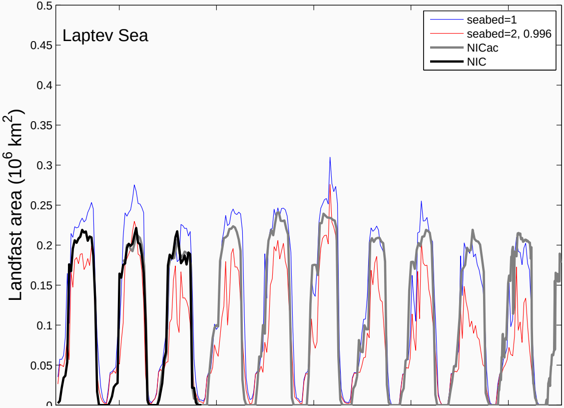



**Figure 6:** Landfast ice extent in the Laptev Sea as simulated the two models compared with observations (NIC and CMC).

# Results

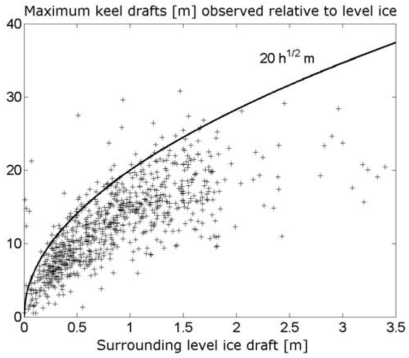



**Figure 7:** Amundrud et al. (2004). Upward looking sonar data from the Beaufort Sea.

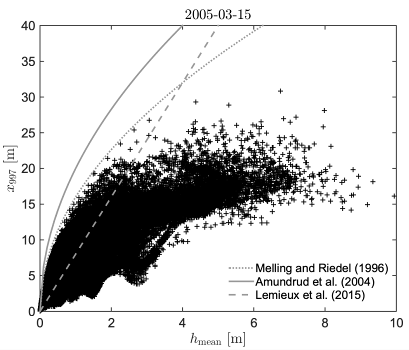
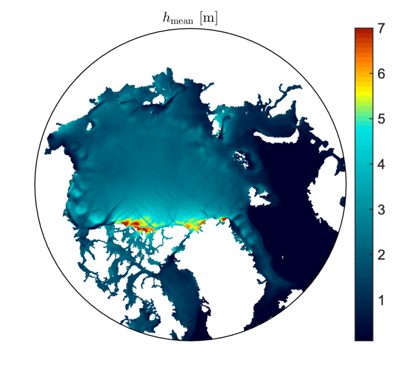
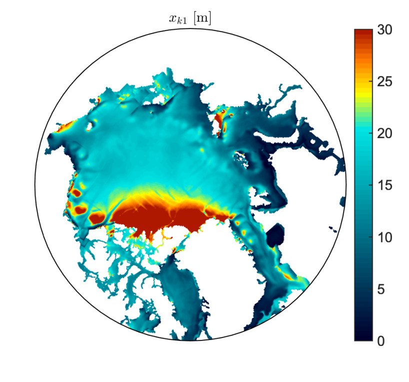


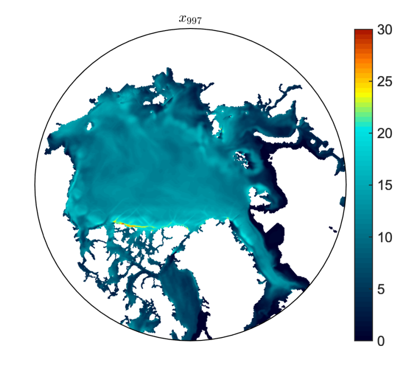

**Figure 8:** $x_{997}$ in (m) as a function of the mean ice thickness in RIOPS on 15 March 2005 across the entire Arctic Ocean.

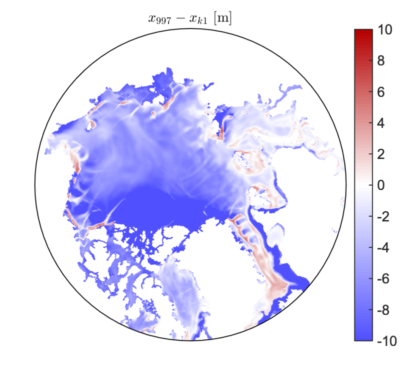
# Results



# Results



# Conclusions and perspectives

- The probabilistic approach based on the ITD better reflect the physical processes.
- Keel depth statistics are well represented by the $99.7^{th}$ percentile of a log-normal distribution having the same mean and variance as the model ITD $\rightarrow$ opportunity to develop a product for the thickest ice keels.
- Leads to similar performances in simulating landfast ice phenology that the previous linear model, with less tuning.
- Discrepancies between model and observations may lead to error identification and model improvement (e.g. mechanical redistribution during ice convergence).
- Potential improvement by using a more realistic bathymetry distribution $B(y)$, for e.g. based on ETOPO data.
- Increasing the number of categories to study mechanical redistribution processes and their effects in constrained or shallow regions.

Merci !