Implementing Landfast Ice in E3SM

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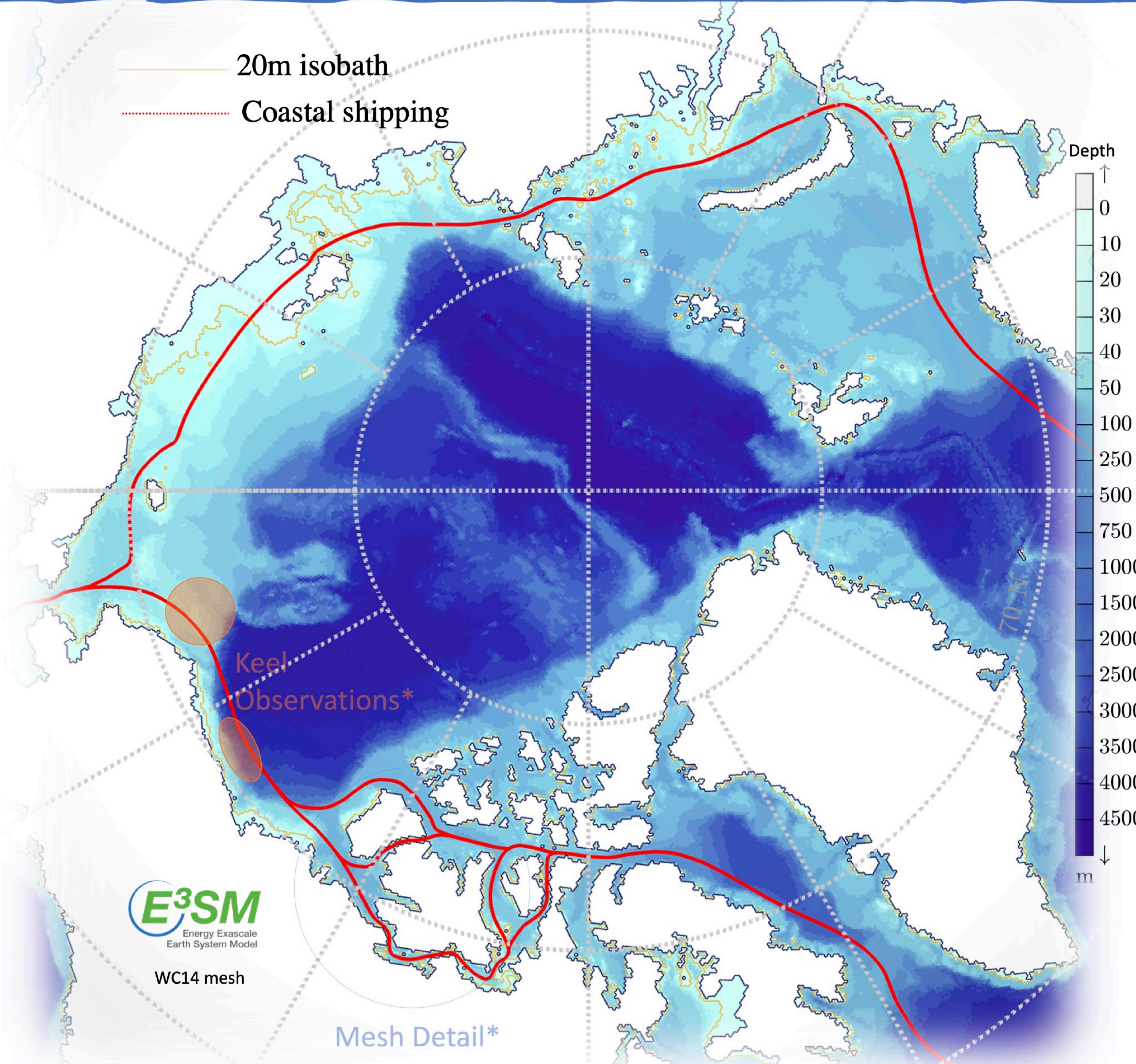
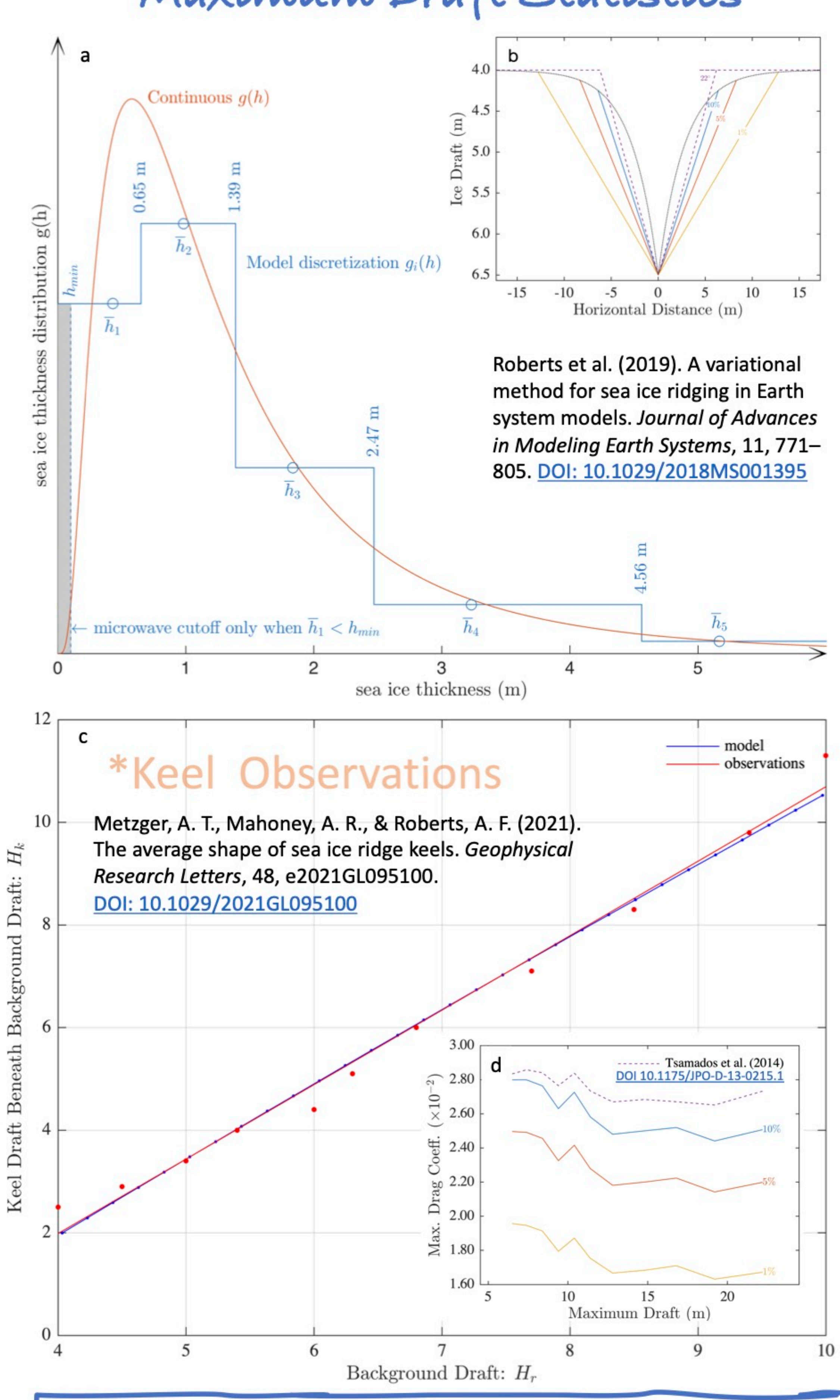
1. Summary

Landfast ice constitutes a significant portion of sea ice mass in the central Arctic and Canadian Archipelago. It is instrumental in protecting coastlines from erosion, limiting coastal shipping, and modulating Arctic Ocean hydrography. I present two different models for landfast ice simulation in E3SM; both models differ from existing landfast ice schemes in order to circumvent significant uncertainties in the stress of keels against the ocean floor. The InteRFACE Empirical Dirichlet Model applies a static boundary condition surrounding grounded ice grid cells based on an analysis of 64,000 ridges off the Alaskan coast, using an empirical relationship between maximum keel depth and deformed rubble. This approach uses results from a variational model to ground sea ice, typically within the 20m isobath, and then constrains ice movement in the vicinity of grounded keels. The empirical model differs from previous landfast ice schemes by using advanced ridge analysis to enforce grounding. The second landfast ice model takes this approach a step further to inversely derive basal stress acting on keels using a full variational model. The models are currently being coded into E3SM, applying global mesh constraints to the native unstructured sea ice grid.



Maximum Draft Statistics



Roberts et al. (2019). A variational method for sea ice ridging in Earth system models. *Journal of Advances in Modeling Earth Systems*, 11, 771–805. DOI: 10.1029/2018MS001395

Metzger, A. T., Mahoney, A. R., & Roberts, A. F. (2021). The average shape of sea ice ridge keels. *Geophysical Research Letters*, 48, e2021GL095100. DOI: 10.1029/2021GL095100

2. Empirical Dirichlet Model

The Empirical Dirichlet Landfast Ice model being implemented in E3SM differs from existing landfast modeling methods by applying a Dirichlet boundary condition such that ice velocity $\boldsymbol{u}(x,t)$ becomes zero according to:

$$\boldsymbol{u}(x,t) = 0 \iff \eta_i(x,t) < H_{max}(x,t)$$

where $\eta_i(x,t)$ is the depth of the ocean:

$$\eta_i(x,t) = \eta_o(x,t)\frac{\eta_i(x,0)}{\eta_o(x,0)}$$

for sea surface height η of the ice and ocean (i,o) models at time t and location x. The latter equation scales η_i to accommodate differences in sea ice and ocean bathymetry due to a minimum limit on the number of layers in a baroclinic ocean model. The maximum keel depth is determined from keel observations

$$H_{max} = H_r(x,t)\left(\frac{dH_k}{dH_r}+1\right)+c$$

for maximum deformed ice draft H_r from the deformed thickness distribution $g(h)$ (Fig a).

Maximum keel draft H_k and interceptor c are derived from linear regression (Figs b and c):

$$H_r = \int_0^\infty \left(h\frac{\rho_i}{\rho_w} + h_s\frac{\rho_s}{\rho_w}\right) g(h)dh$$

This follows from Metzger et al. (2021) where the maximum keel draft is relative to the background deformed ice field, not undeformed ice floes. The corollary of the Dirichlet boundary condition is that ice body forces $\boldsymbol{F}_b$ for mass per unit area m and internal stress $\overline{\boldsymbol{\sigma}}$ assures that

$$m\frac{d\boldsymbol{u}}{dt} = \boldsymbol{F}_b + \nabla\cdot\overline{\boldsymbol{\sigma}} = \boldsymbol{0}$$

Which occurs because the under-ice stress $\boldsymbol{\tau}_w$ balances all other body forces from wind $\boldsymbol{\tau}_a$, Coriolis, and the sea surface gradient due to friction on the sea floor, included in $\boldsymbol{\tau}_w$:

$$\boldsymbol{F}_b = \boldsymbol{\tau}_a + \boldsymbol{\tau}_w + mf\boldsymbol{k}\times\boldsymbol{u} - mg\nabla\eta_i$$

This model is the most justifiable because there are many aspects of $\boldsymbol{\tau}_w$ (e.g. Fig. d) only vaguely known, and so we avoid parametric tuning that is difficult to justify, instead using boundary conditions constrained by measurement.

3. Variational Model

In the Empirical Dirichlet Model, we utilized outcomes of the variational ridging model of Roberts et al. (2019). In a more advanced application, and in collaboration with the E3SM project, we plan to use the full variational ridging model that generates ridges explicitly as part of the thickness distribution $g(h)$, so that H_{max} is modeled rather than observationally-derived. The variational approach permits explicit determination of the portion of $\boldsymbol{\tau}_w$ due to keels dragging on the ocean floor, thereby allowing inverse determination of $\overline{\boldsymbol{\sigma}}$ needed to maintain stationary ice in the landfast area A (Figs e, f):

$$\int_A \left(-m\frac{d\boldsymbol{u}}{dt} + \boldsymbol{F}_b + \nabla\cdot\overline{\boldsymbol{\sigma}}\right)\cdot\delta x\, dA = 0$$

This approach becomes possible because the form drag of ridges in $\boldsymbol{\tau}_w$ is explicitly represented as shown in Fig. d excluding, for example, 1, 5, and 10% of those making up the average cusp-shaped keel (Fig. b). Using this approach, the above variational condition results from the Dirichlet boundary condition. The place where this is likely to have the largest impact is in the Canadian Archipelago, where pure grounding is limited, heuristically indicated by the 20m isobath in the main map.

Constraints Visualized