Task 3.4

Improve the representation of surface heat flux in the Arctic

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Goal: Two targets for improving the Arctic surface energy budget

Stability relations in strongly-stable stratification:

- *Known* to be large source of bias (e.g. *Davy et al.*, 2014)
- Existing formulations not based on Arctic observations, long-lived stable boundary layers
- Use SHEBA data – long-period observations over sea-ice – to build empirical relations

Leads in the sea ice:

- *Unknown* climate impact
- *Needs* high-resolution, turbulence-resolving models to determine fluxes
- *Needs* high-resolution observations of lead-width distribution

Target 1: Stability functions

- Stability functions determine *vertical gradients* in wind, temperature, water vapor as a function of *atmospheric stability*
- *Empirical* formulations
- SHEBA data – winter-long observations of fluxes at multiple heights
- New formulations for stability functions

$$\frac{\kappa z}{u_*}\frac{\mathrm{d}U}{\mathrm{d}z} = \boxed{\varphi_m(\zeta)},$$

$$\frac{\kappa z}{\theta_*}\frac{\mathrm{d}\theta}{\mathrm{d}z} = \boxed{\varphi_h(\zeta)},$$

$$U(z) = \frac{u_*}{\kappa}\left[\ln\frac{z}{z_\mathrm{o}} \boxed{- \Psi_m\left(\frac{z}{L}\right) + \Psi_m\left(\frac{z_\mathrm{o}}{L}\right)}\right],$$

$$\theta(z) - \theta_\mathrm{o} = \frac{\theta_*}{\kappa}\left[\ln\frac{z}{z_\mathrm{ot}} \boxed{- \Psi_h\left(\frac{z}{L}\right) + \Psi_h\left(\frac{z_\mathrm{ot}}{L}\right)}\right].$$

Implementation plan: stability relations

- Adjustment to surface schemes – relating first atmospheric model level to surface.
- Embedded in Sea-ice (*CICE*) and Land (*CLM)* model components
- Functional forms:

$$\varphi_{m\ \mathrm{SHEBA}} = 1 + \frac{a_m \zeta (1+\zeta)^{1/3}}{1 + b_m \zeta} \equiv 1 + \frac{6.5\zeta(1+\zeta)^{1/3}}{1.3+\zeta},$$

$$\varphi_{h\ \mathrm{SHEBA}} = 1 + \frac{a_h \zeta + b_h \zeta^2}{1 + c_h \zeta + \zeta^2} \equiv 1 + \frac{5\zeta + 5\zeta^2}{1 + 3\zeta + \zeta^2},$$

Old forms:

$$\psi_m = \psi_s = -\left[0.7\Upsilon + 0.75\left(\Upsilon - 14.3\right)\exp\left(-0.35\Upsilon\right) + 10.7\right].$$

- Integrated forms:

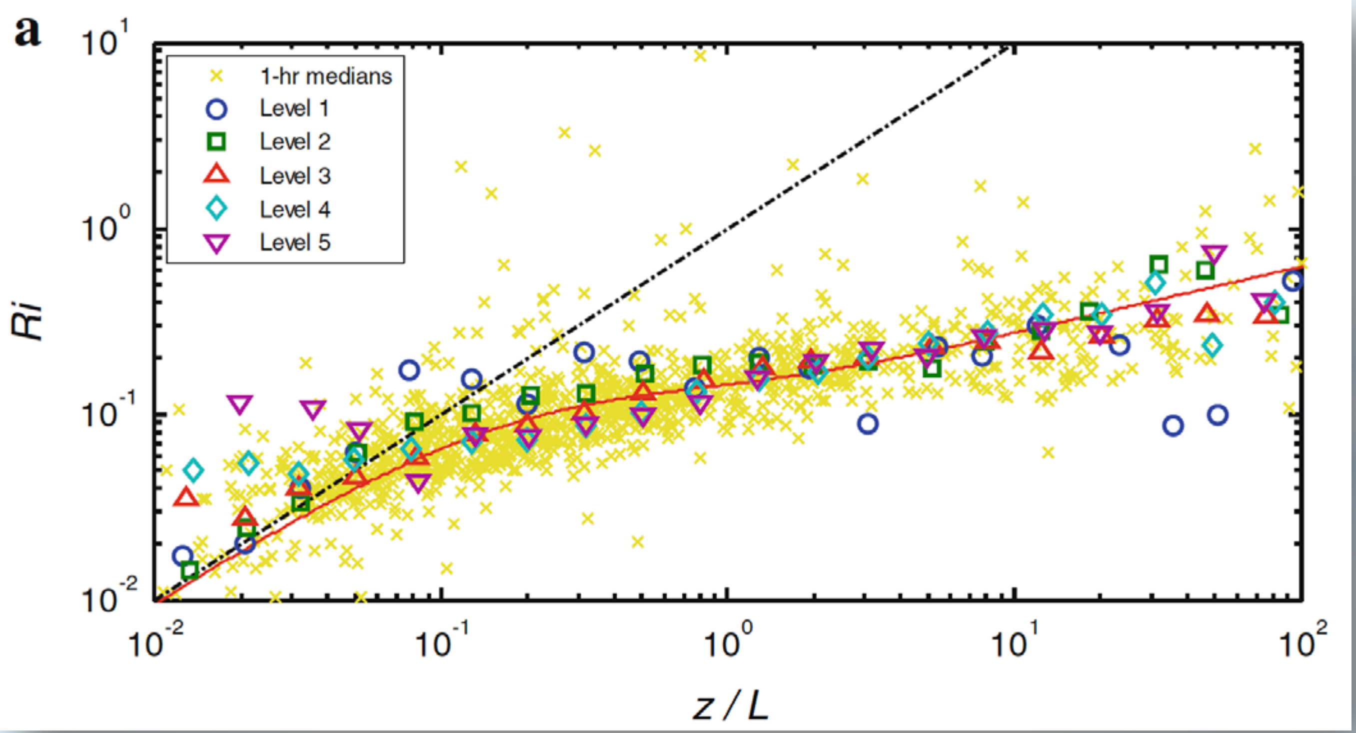
$$\Psi_{m\ \mathrm{SHEBA}}(\zeta) = -\frac{3a_m}{b_m}(x-1) + \frac{a_m B_m}{2b_m}\left[2\ln\frac{x+B_m}{1+B_m} - \ln\frac{x^2 - xB_m + B_m^2}{1 - B_m + B_m^2} + 2\sqrt{3}\left(\arctan\frac{2x-B_m}{\sqrt{3}B_m} - \arctan\frac{2-B_m}{\sqrt{3}B_m}\right)\right],$$

$$\Psi_{h\ \mathrm{SHEBA}}(\zeta) = -\frac{b_h}{2}\ln\left(1 + c_h\zeta + \zeta^2\right) + \left(-\frac{a_h}{B_h} + \frac{b_h c_h}{2B_h}\right) \times \left(\ln\frac{2\zeta + c_h - B_h}{2\zeta + c_h + B_h} - \ln\frac{c_h - B_h}{c_h + B_h}\right),$$

- Cross-validate against *independent* field campaign *observations*

Implementation plan: NorESM

- In NorESM, we replace the existing stability functions in the Sea-ice (*CICE*) and Land (*CLM)* model components, with forms derived from SHEBA data. These converge to the current scheme for weakly-stable stratification:



Target 2: Leads in ice

Sensible heat flux from leads can be ~300 W m^{-2}

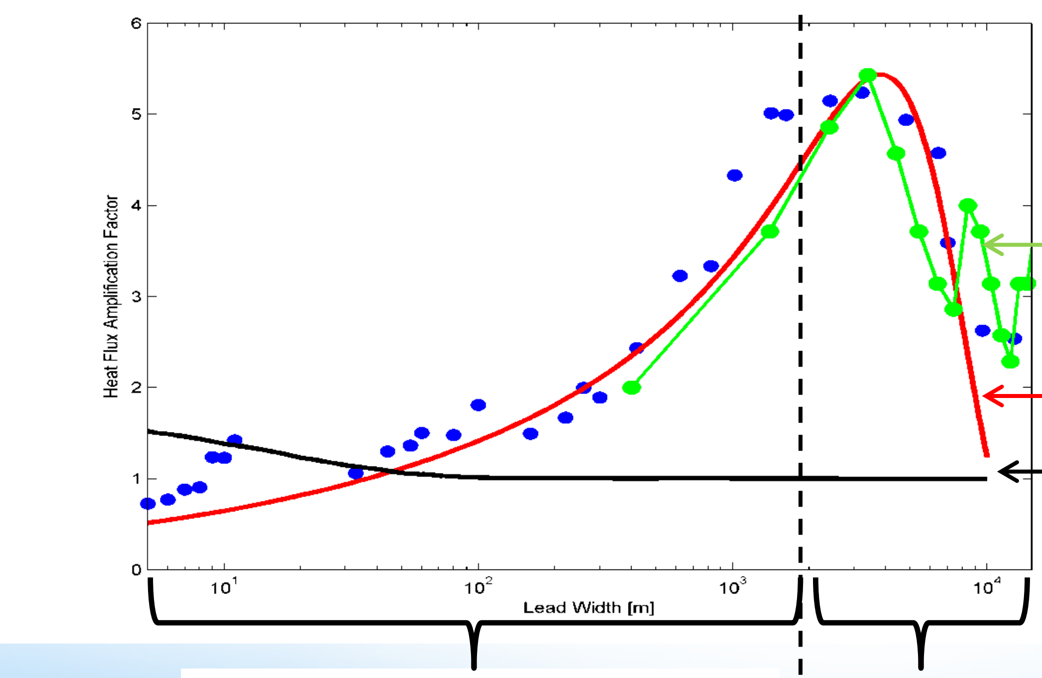
Annual average over Arctic ~3 W m^{-2}

Existing assumption:

Highest fluxes per-unit-area in narrowest leads

Does not account for 3-dimensional turbulent structures

Convection over leads from turbulence resolving (LES) simulations

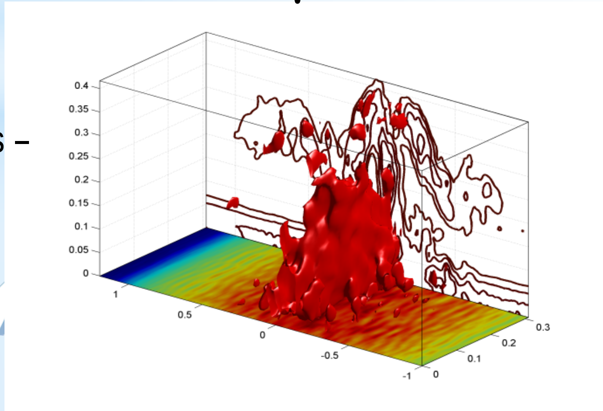


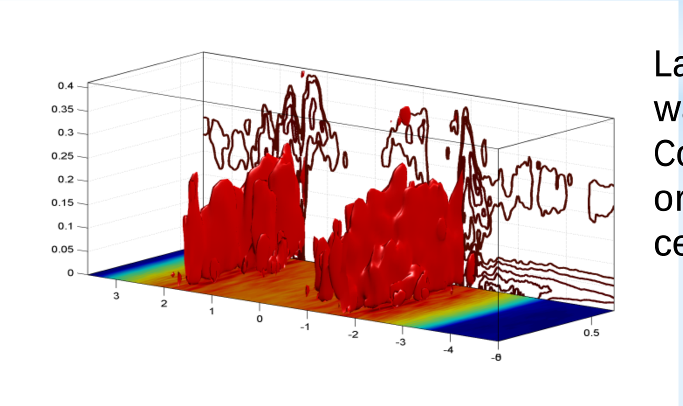
Observations (Baltic Sea data)

Turbulence data (approximation of LES runs)

Parameterizations (flux-gradient approach)

Small open water patches – Convection is organized in chimneys

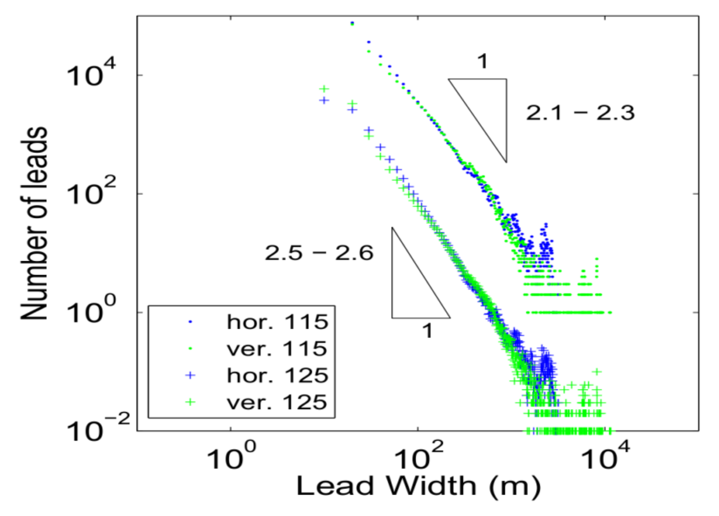


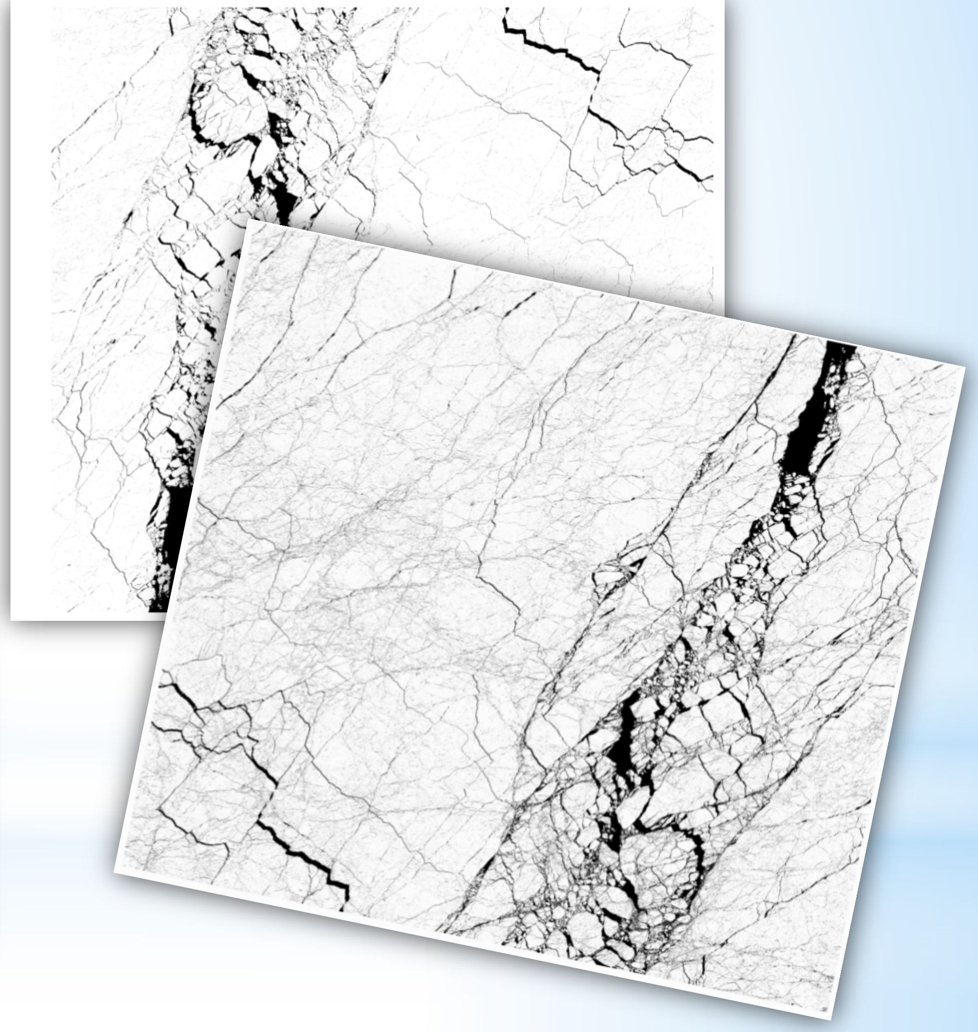


Large open water patches – Convection is organized in cells

Observations of leads in sea-ice

- SPOT satellite images
- Distribution of Lead widths has been established from observations:

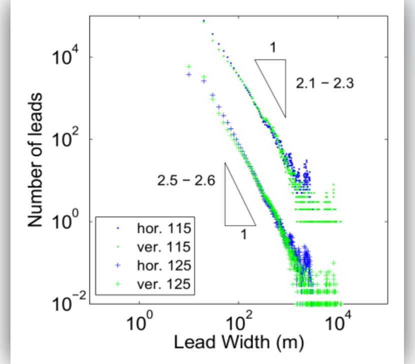




Heat fluxes through leads

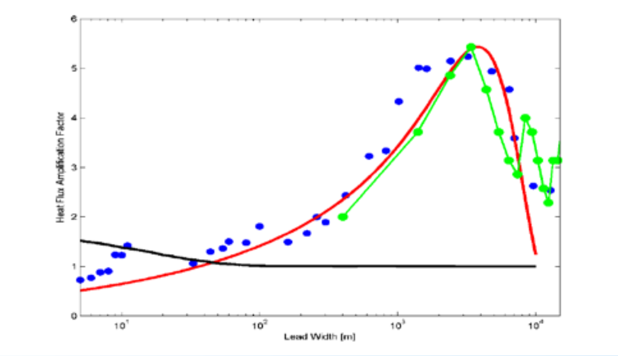
Probability function from *observations:*

$$P(x) = \frac{a-1}{L_0}\left(\frac{x}{L_0}\right)^{-a}$$



Heat flux from *Large eddy simulation:*

$$A(x) = 5\left(\frac{x}{\lambda_{CBL}}\right)^{1/3} \exp\left(\frac{-\left({x}/{\lambda_{CBL}} - 1\right)^2}{4.84}\right)$$



Net effect:

$$\hat{A} = \int_{L_0}^{\infty} A(x)P(x)dx$$

Total effect = expectation value over valid range

Heat fluxes through leads: controlling parameters

$$\hat{A} = \int_{L_0}^{\infty} 5\left(\frac{x}{\lambda_{CBL}}\right)^{1/3} \exp\left(\frac{-\left({}^{x}/_{\lambda_{CBL}} - 1\right)^{2}}{4.84}\right) \frac{a-1}{L_0}\left(\frac{x}{L_0}\right)^{-a} dx$$

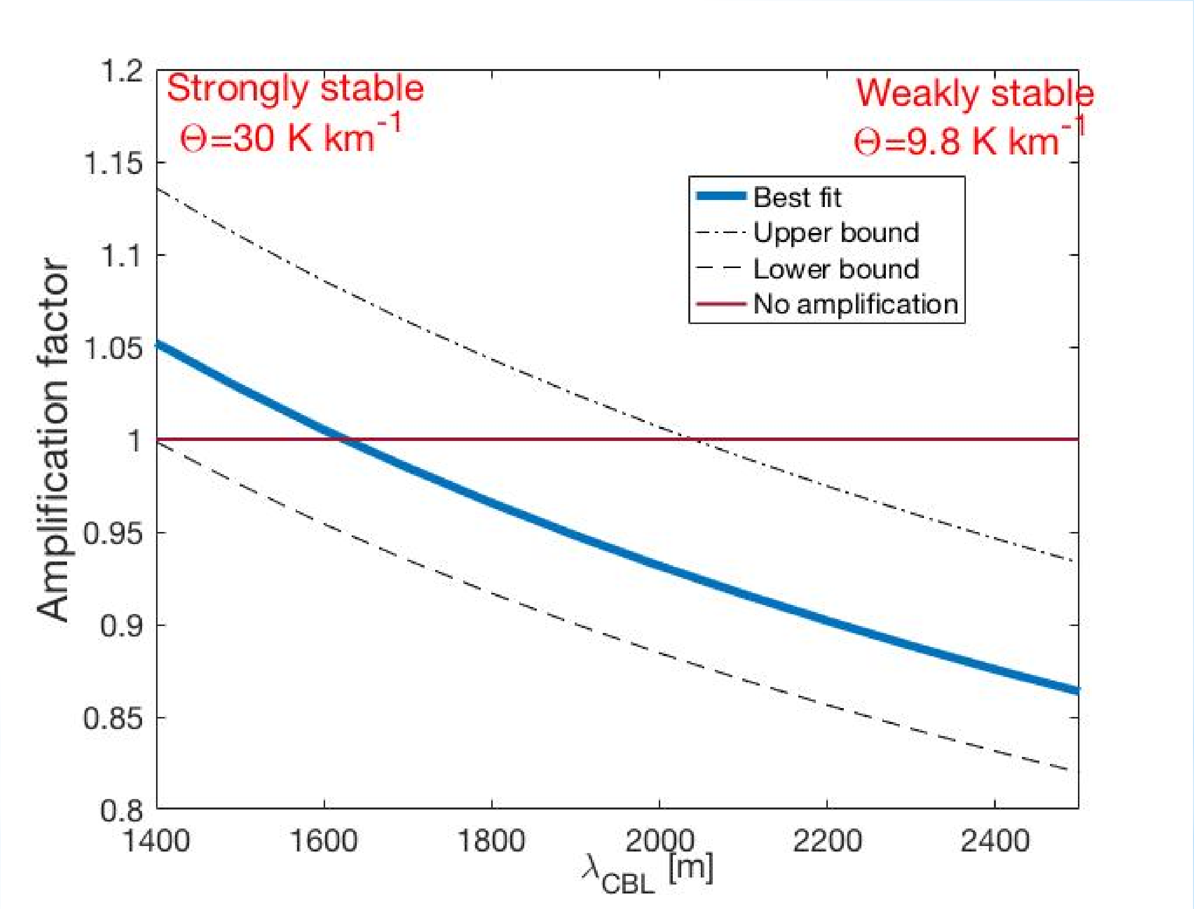
- $a = \begin{bmatrix} 2.1 & 2.3 \\ 2.5 & 2.6 \end{bmatrix}$ is a coefficient from the size distribution of leads and depends upon the method used to analyse the SPOT images (blue vs red)

- $\lambda_{CBL} = [1400 \;\; 2500]$ depends on the background stability of the atmosphere i.e. state dependent variable

- $L_0 = 10m$ is the minimum lead width for which the power law and flux-relationship applies. This is based upon the resolution of the SPOT images used to establish the distributions.

Net amplification of sensible heat flux

- Numerical integration yields ->
- **Large uncertainty** comes from the exponent in the *size distribution*
- Do functional forms extended to leads widths below 10m?
- *Unknown* uncertainty due to functional forms chosen for both heat flux and size distribution.

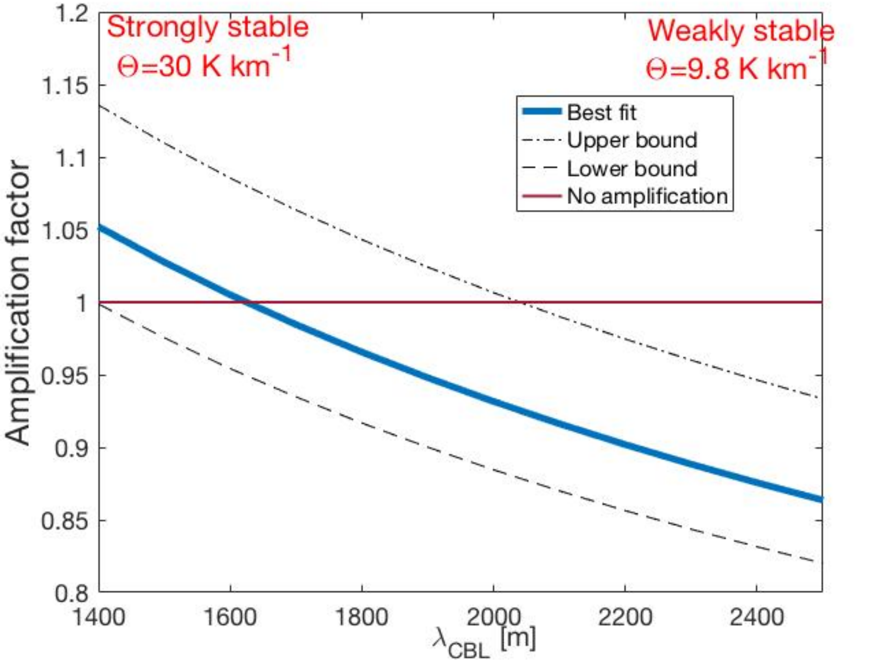


Implementation: Amplification of sensible heat flux from open water

- $\hat{A}$ - Net amplification of the open water surface sensible heat flux (Amplification factor)

- λ_{CBL} [m] - Length scale for the atmospheric boundary layer dependent upon the stability.

- θ [K m^{-1}] – Background atmospheric stability calculated at a height of around 300 m.



$$\hat{A} = a{\lambda_{CBL}}^2 + b\lambda_{CBL} + c,$$

$$\lambda_{CBL}=3008 - 52381\,\theta$$

a= 6.012x10^{-8}, b= 4.036x10^{-4}, c=1.4979

Implementation: Adjusting for sea ice concentration

Now we have our amplification factor, $\hat{A}$, to be applied to open water surface sensible heat fluxes.

But we only want to apply it when we think the open water is due to the presence of leads.

Use the sea ice concentration to determine if the open water is due to leads:

– assume open water is at least partly due to leads above 70% ice cover

– assume all open water is due to leads above 90% ice cover.

- Scale linearly in the range 70%-90%

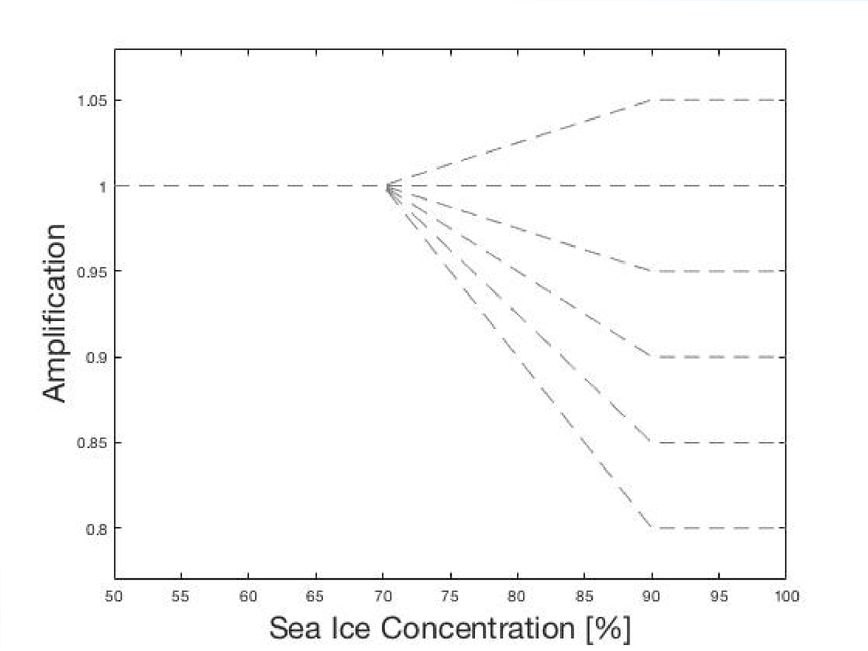


Photo credit: Kathryn Hansen/NASA

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