A climatology of thermodynamic vs. dynamic Arctic wintertime sea ice thickness effects during the CryoSat-2 era

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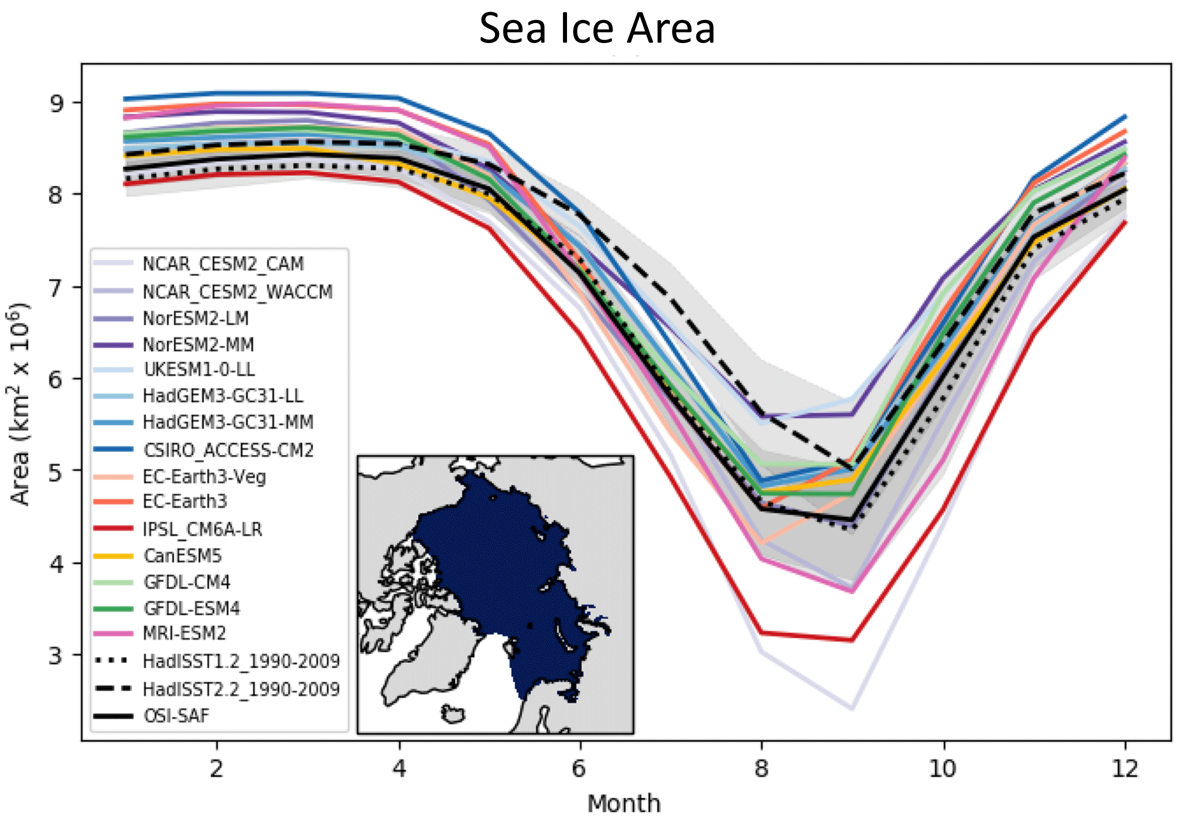
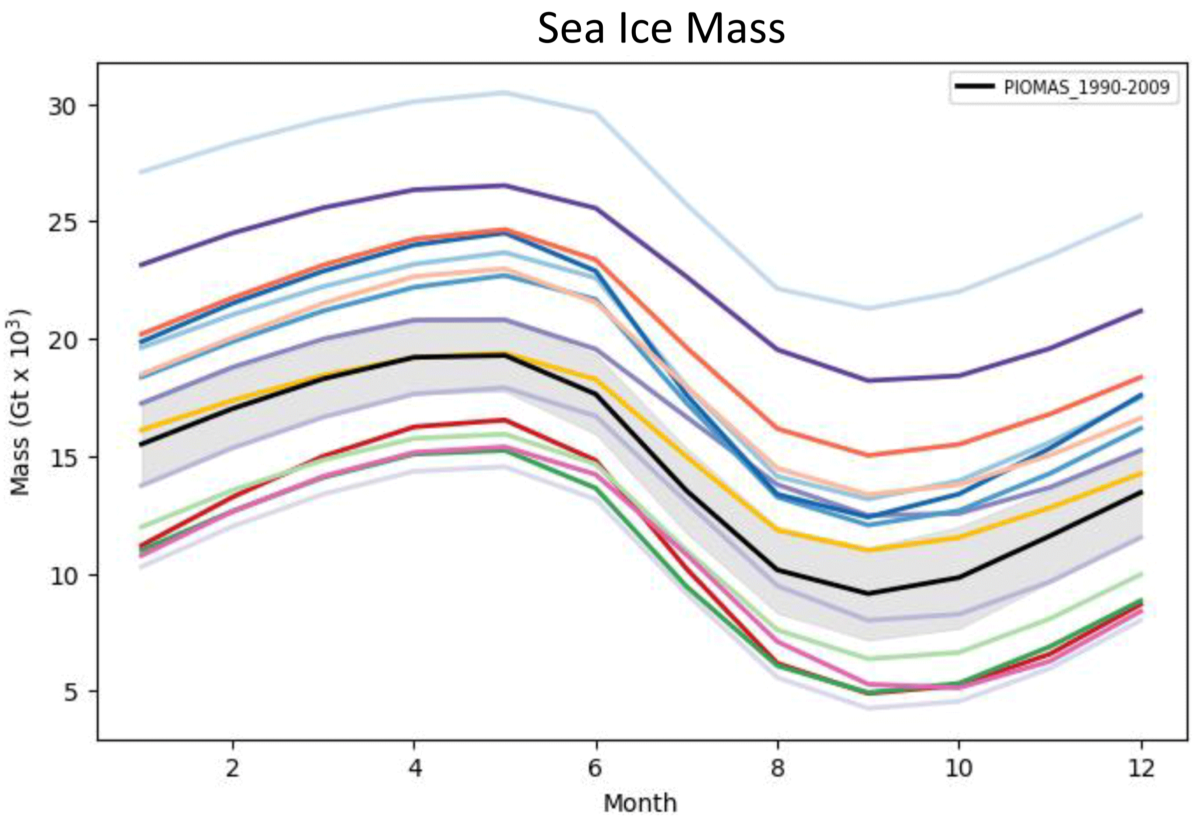
Anheuser, J., Liu, Y., and Key, J. R.: A climatology of thermodynamic vs. dynamic Arctic wintertime sea ice thickness effects during the CryoSat-2 era, The Cryosphere, 17, 2871–2889, https://doi.org/10.5194/tc-17-2871-2023, 2023.

CMIP6 Models (1990-2009 monthly mean)





Keen et al., 2021

Sea ice thickness growth (simplified) “governing” equation

$$\frac{\partial H}{\partial t} = \underbrace{f(t, H, \mathbf{x})}_{\text{Thermodynamics}} \underbrace{- \nabla \cdot (\mathbf{u}H)}_{\text{Dynamics}}$$

H is ice thickness, t is time, **x** is location, **u** is drift velocity

Thermodynamics: ice thickness change through phase change

Dynamics: ice thickness change through relative motion of ice parcels (compressible advection)

Sea ice thickness growth (simplified) "governing" equation

$$\frac{\partial H}{\partial t} = \underbrace{f(t, H, \mathbf{x})}_{\text{Thermodynamics}} \underbrace{- \nabla \cdot (\mathbf{u}H)}_{\text{Dynamics}}$$

- Affected by differing mechanisms in a changing climate
- Large scale observations of each process and their comparison to climate models are needed but lacking

Science Question:

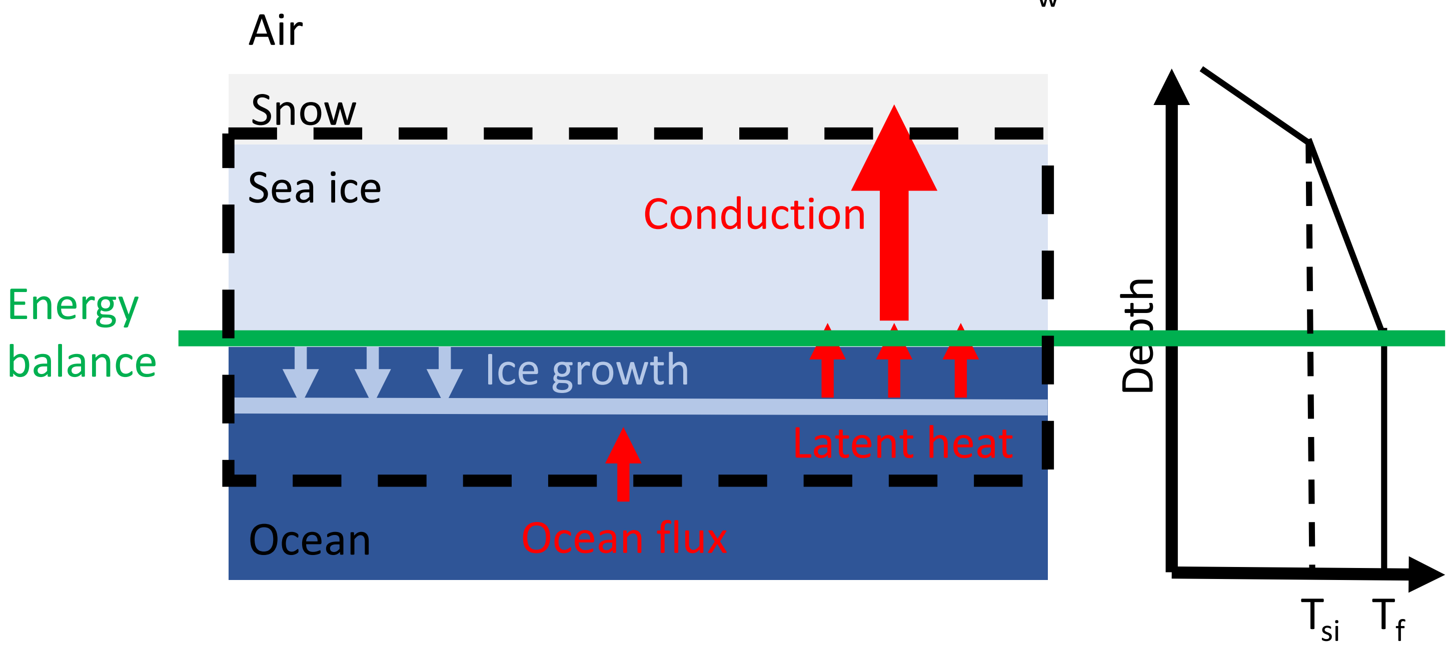
What are relative effects of dynamic and thermodynamic sea ice thickness processes in the Arctic?

Stefan's Law: simple sea ice thermodynamics

Latent heat of fusion　　Conduction　　Ocean Flux

$$\rho_i L \frac{\partial H}{\partial t} = \frac{\kappa_i}{H}(T_f - T_{si}) - F_w$$

ρ=ice density, L=latent heat, H=ice depth, k=ice conductivity, T_f=ice freezing point, T_{si}= snow--ice temperature, F_w = ocean heat flux to ice



Allow instantaneous relationship!

Neglect:

- Horizontal conduction
- Thermal inertia
- Internal heat sources

Stefan (1891), Lepperanta (1993)

Stefan’s Law Integrated Conducted Energy (SLICE)

Passive microwave retrieved snow—ice interface temp. (Kilic et al., 2019)

Stefan’s Law solution

$$H = \sqrt{H_0^2 + \delta t \frac{2\kappa_{\mathrm{eff}}}{\rho_{\mathrm{i}} L}(T_{\mathrm{f}} - \boxed{T_{\mathrm{si}})} - \delta t \frac{F_{\mathrm{w}}}{\rho_{\mathrm{i}} L}}$$

Attributes

- Retrieves instantaneous thermodynamic growth
- Daily, basin-wide coverage
- F_w = 2 w/m^2

Caveats

- Requires initial condition (H_0) to retrieve absolute thickness
- No melt or sunlight! Growth season only
- >95% ice concentration only

Anheuser et al., 2022

Use CryoSat-2 and SLICE to estimate weekly dynamics

$$\frac{\partial H}{\partial t} = \underbrace{f(t, H, \mathbf{x})}_{\text{Thermodynamics}} \underbrace{- \nabla \cdot (\mathbf{u}H)}_{\text{Dynamics}}$$

$$\frac{\partial [CryoSat{-}2]}{\partial t} = [\text{SLICE}] + \underbrace{[\text{residual}]}_{\text{Dynamics}}$$

CryoSat-2: Alfred Wegener Institute (AWI) CS2SMOS

- **weekly CS2/SMOS combination sea ice thickness product**
- **Covers 2010-2021**
- **Ricker et al. (2017)**

Decompose dynamics into advection and deformation

Dynamics

$$\frac{\partial H}{\partial t} = f(t, H, \boldsymbol{x}) - (\nabla H) \cdot \boldsymbol{u} - H(\nabla \cdot \boldsymbol{u})$$

Advection   Deformation

Dynamics (Eulerian)

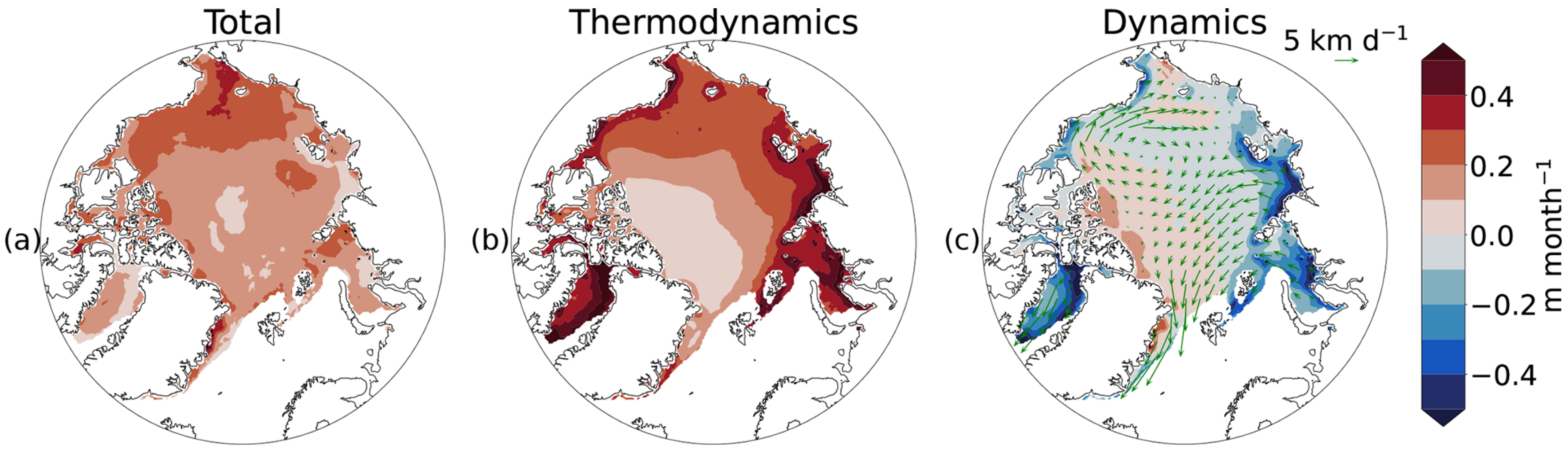
$$\frac{\partial [CryoSat{-}2]}{\partial t} = \text{[SLICE]} - [(\nabla CryoSat - 2) \cdot \boldsymbol{mot.vec.}] - \text{[residual]}$$

Deformation
(Lagrangian dynamics)

Motion vectors

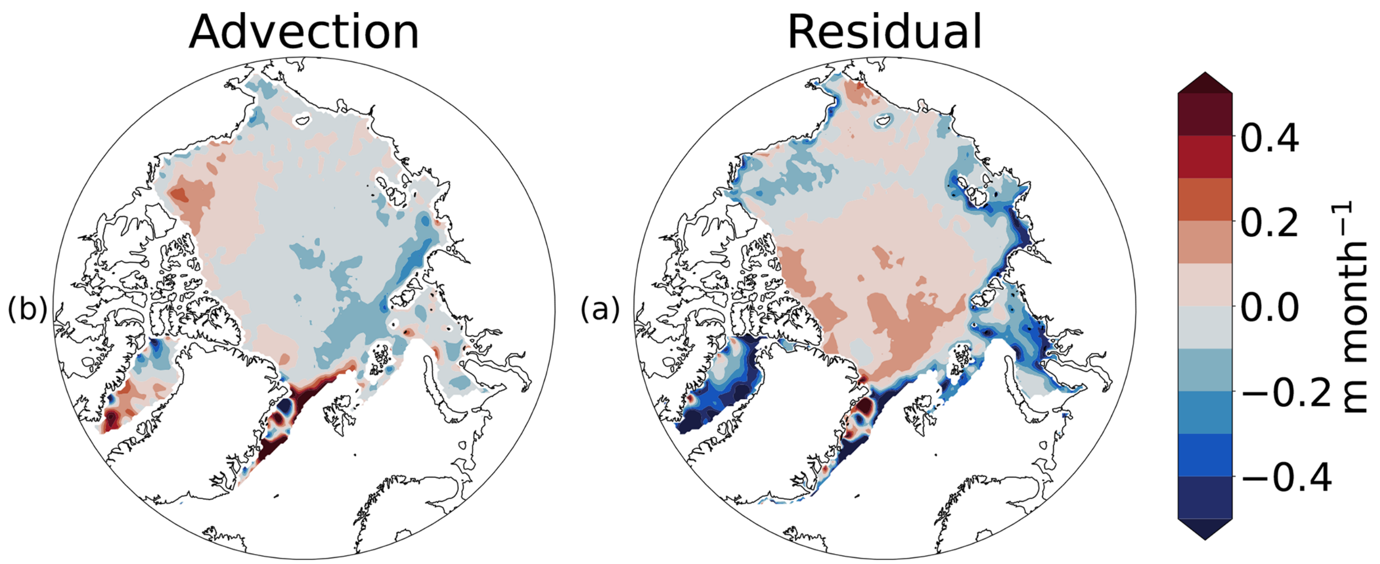
- **Approximate advection term with CS2 thickness field and motion vector**
- **Use satellite-based motion vector product (Tschudi et al., 2019)**

2010-2021 wintertime mean



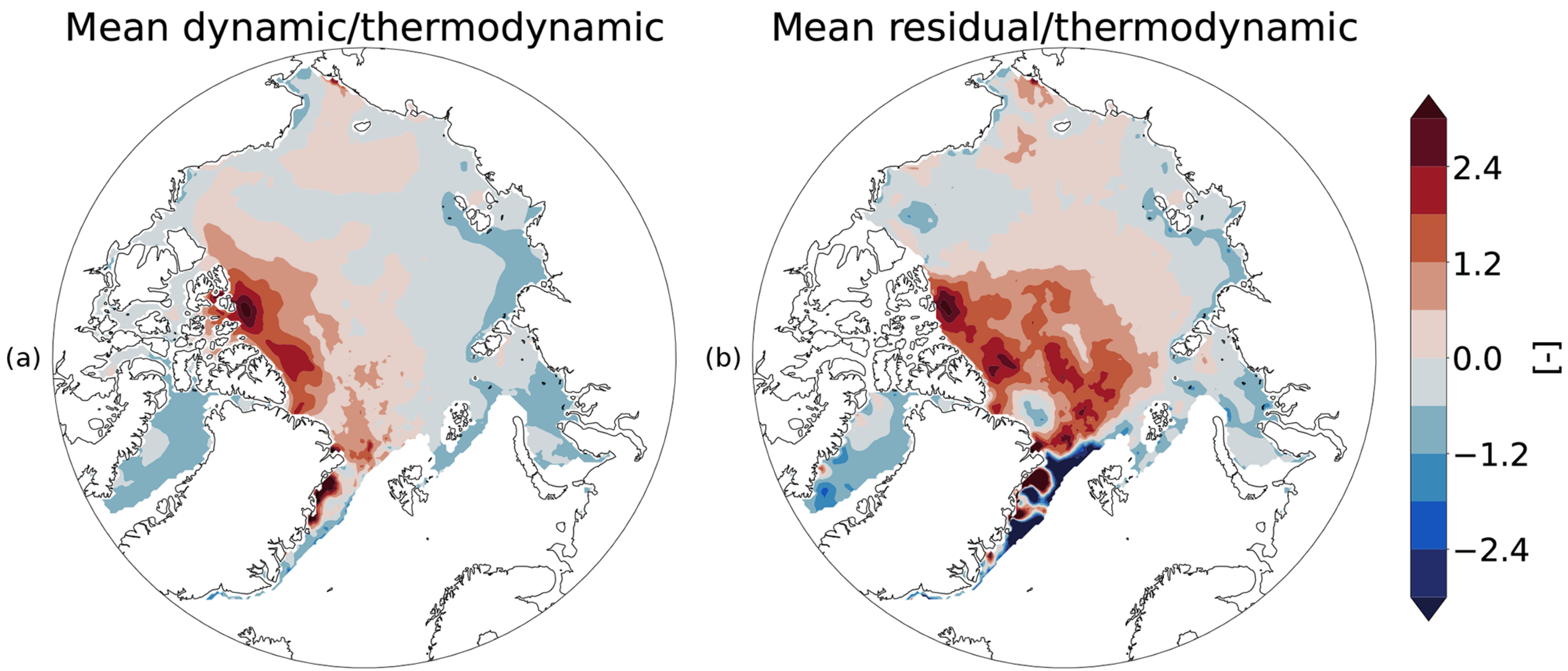
- **Thermodynamic growth highest where ice is thinnest**
- **Dynamics increases thickness north of Canadian Archipelago (CAA) and eastern Siberia**

2010-2021 wintertime mean



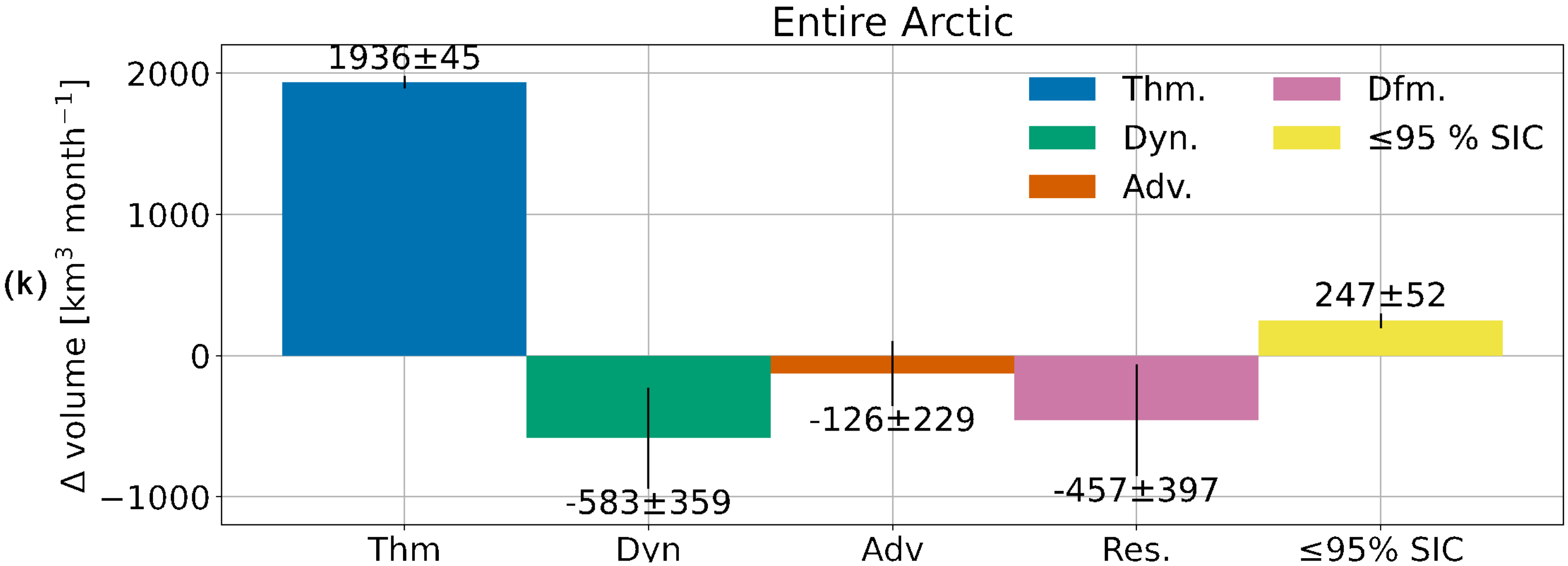
- **BG: advects thick ice towards Alaskan coast where divergence/lead formation reduces thickness, ice is deposited/ridges north of eastern Siberia**
- **TD: advects thinner ice towards CAA, ridging along drift increases thickness**

Dynamics relative to thermodynamics



Some regions are dominated by dynamics, with dynamics more than doubling thermodynamics

Dynamics are -30% of thermodynamics in basin-wide mean



Close agreement with Keen et al., 2021 and Ricker et al., 2021

Conclusions

- Use SLICE and CryoSat-2 to estimate thermo. and dyn. effects
- Dyn. are -30% of thermo. in basin-wide mean, agrees with literature
- Basin-wide, 25km Eulerian, sub-seasonal temporal resolution, and long-term observations expands on literature
- BG: negative deformation/leading in westward leg and positive deformation/ridging eastern Siberian coast and eastward leg
- TD: negative advection coupled with positive deformation/ridging
- Dynamics and deformation effects account for 2x thermodynamic growth in some regions

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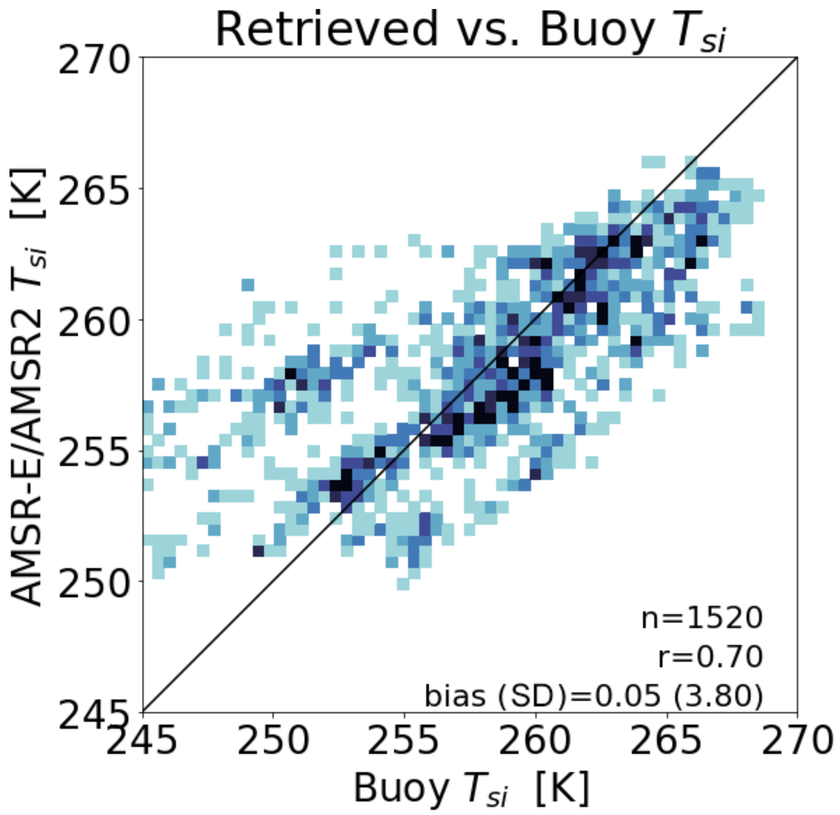
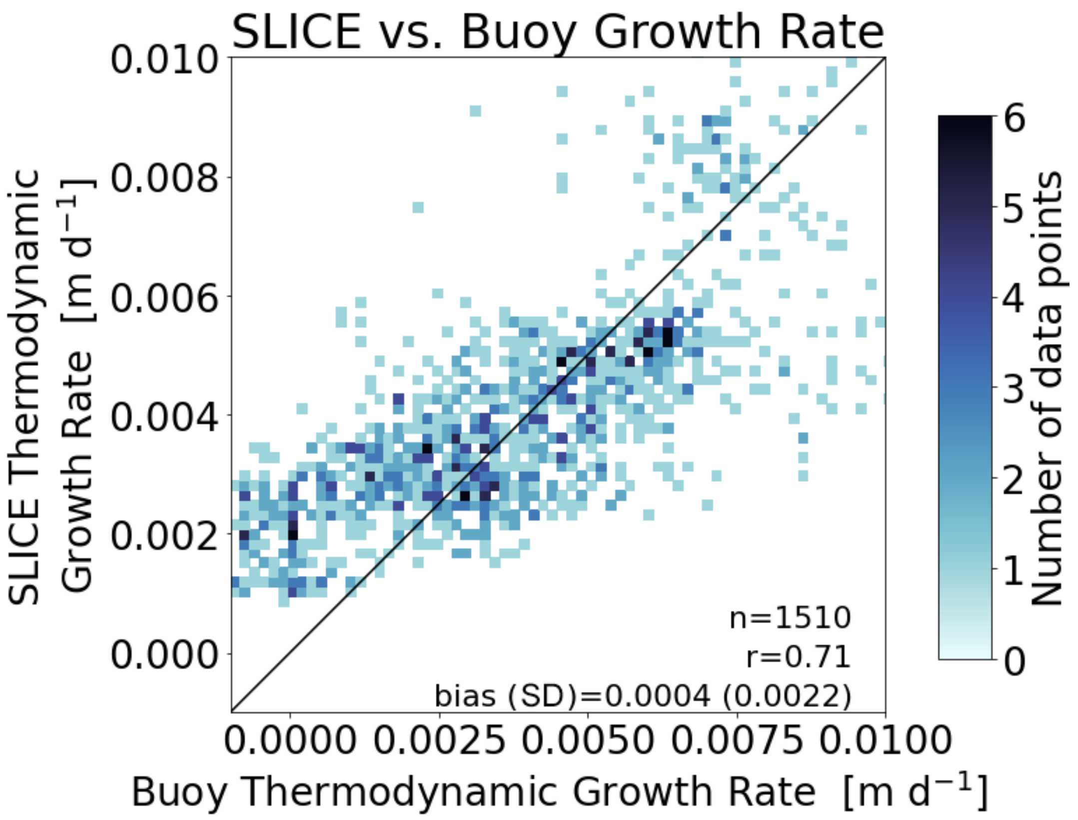
SLICE compares well with buoys



(a)



(b)

Uncertainty