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Title: Probing processes at the base of the Antarctic Ice Sheet

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Probing processes at the base of the Antarctic Ice Sheet

Carolyn Branecky Begeman, Los Alamos National Laboratory

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E3SM Energy Exascale Earth System Model

SciDAC Scientific Discovery through Advanced Computing

CSES Los Alamos

UC SANTA CRUZ

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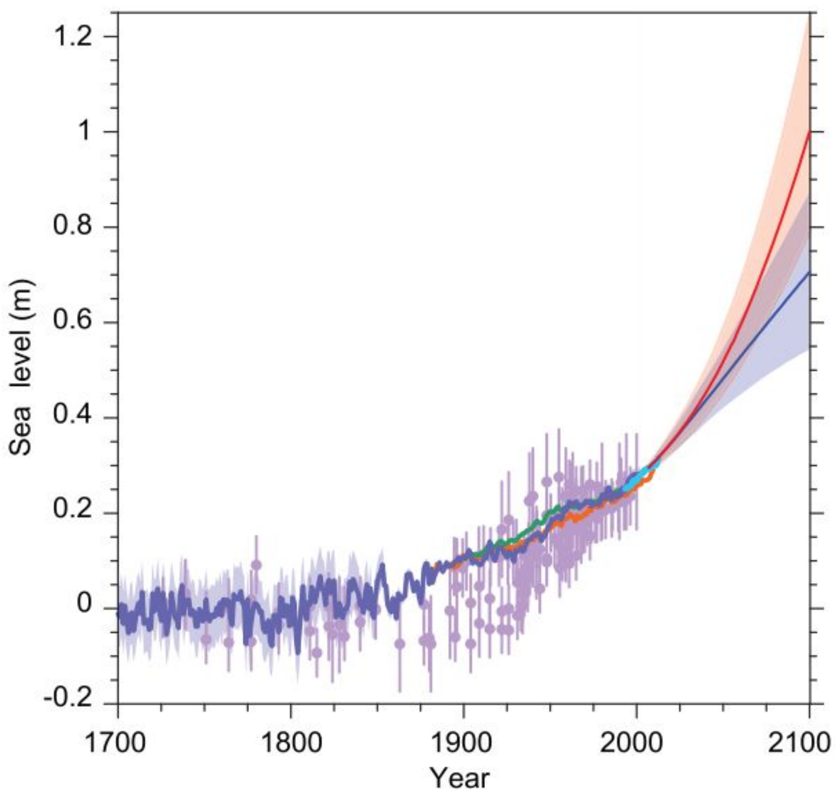
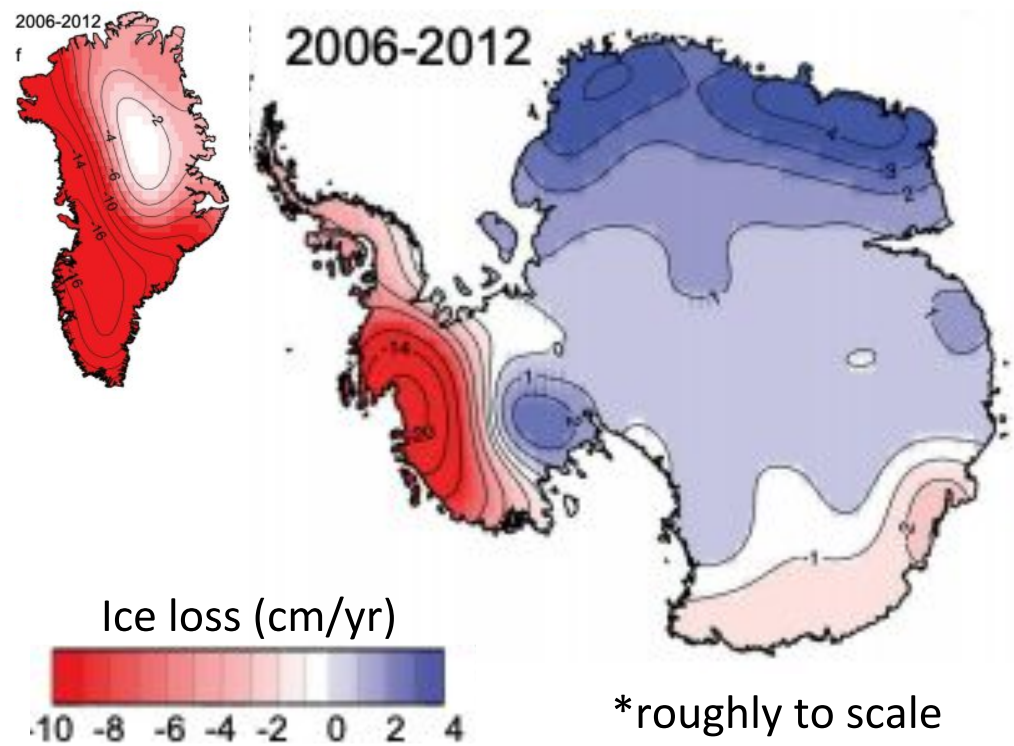
NSF

How much will sea levels rise in the 21st century?
^ due to ice sheet mass loss





*roughly to scale

IPCC AR5, reprinted from Velicogna, 2009

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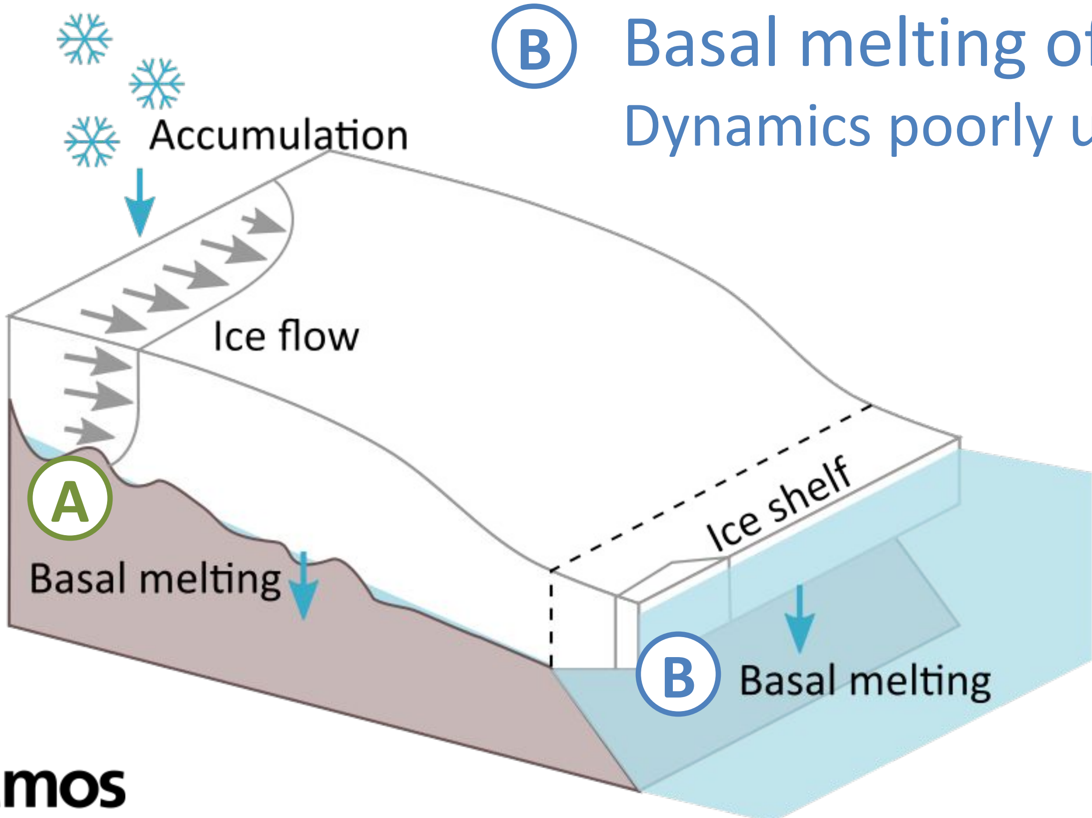
Predicting ice mass loss with an ice sheet model

Ⓐ Basal melting of ice on land:
Dynamics understood but geologic information lacking

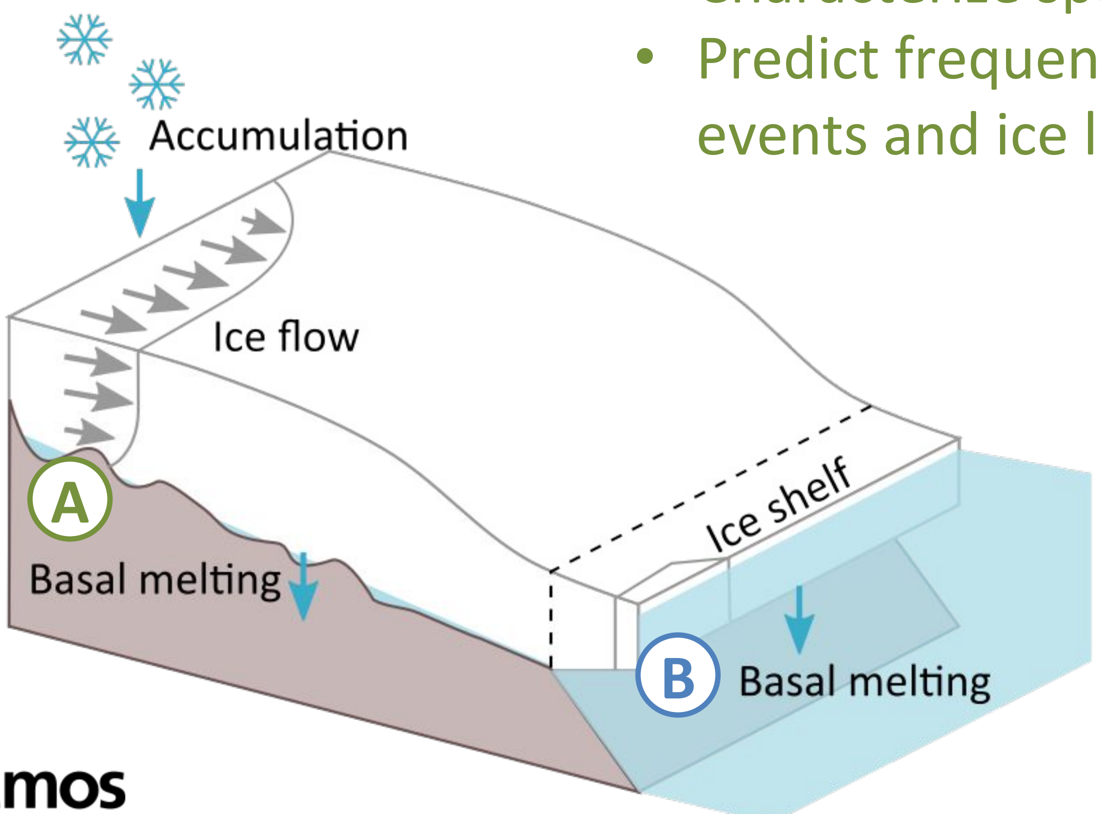
Ⓑ Basal melting of ice over ocean:
Dynamics poorly understood



My work toward improving predictions of ice mass loss

A Basal melting of ice on land (PhD)

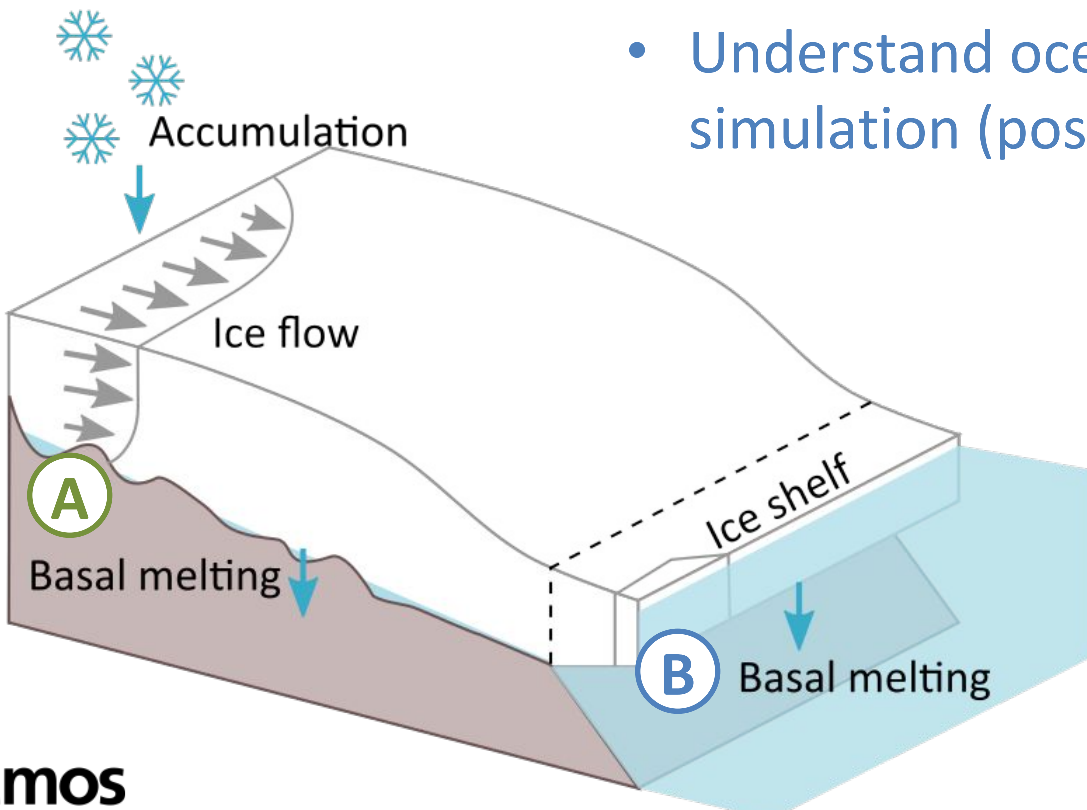
- **Constrain with observations of geothermal flux**
- Characterize spatial variability of geologic processes
- Predict frequency relationships between magmatic events and ice loss



My work toward improving predictions of ice mass loss

Ⓑ Basal melting of ice over ocean

- Constrain with observations of melt rate and local ocean conditions (PhD)
- Understand ocean dynamics through large-eddy simulation (postdoc)



E3SM Energy Exascale Earth System Model

Fully-coupled interactions between i
sheet and ocean model

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Quantify uncertainty in ice sheet m
balance from different sources

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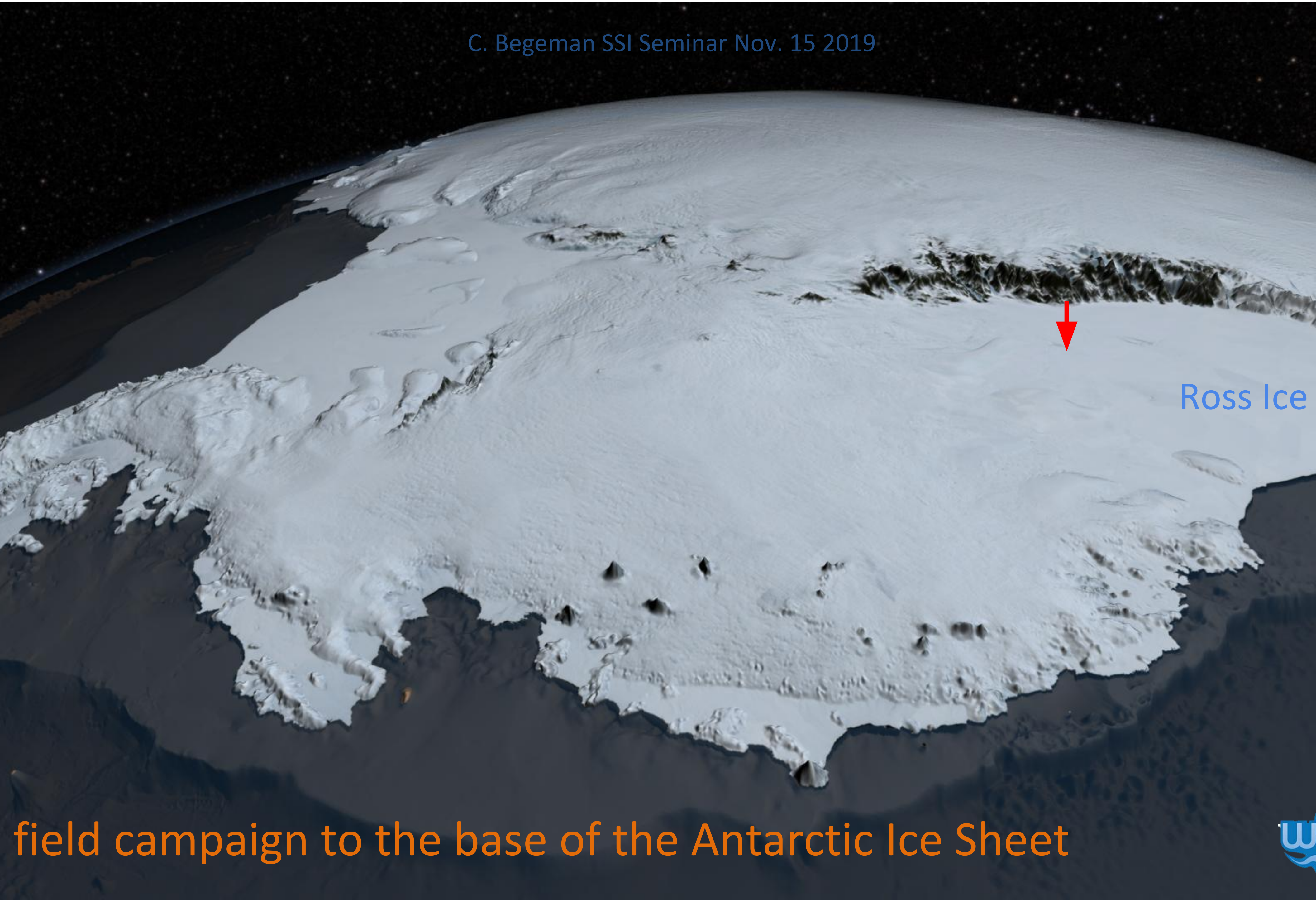
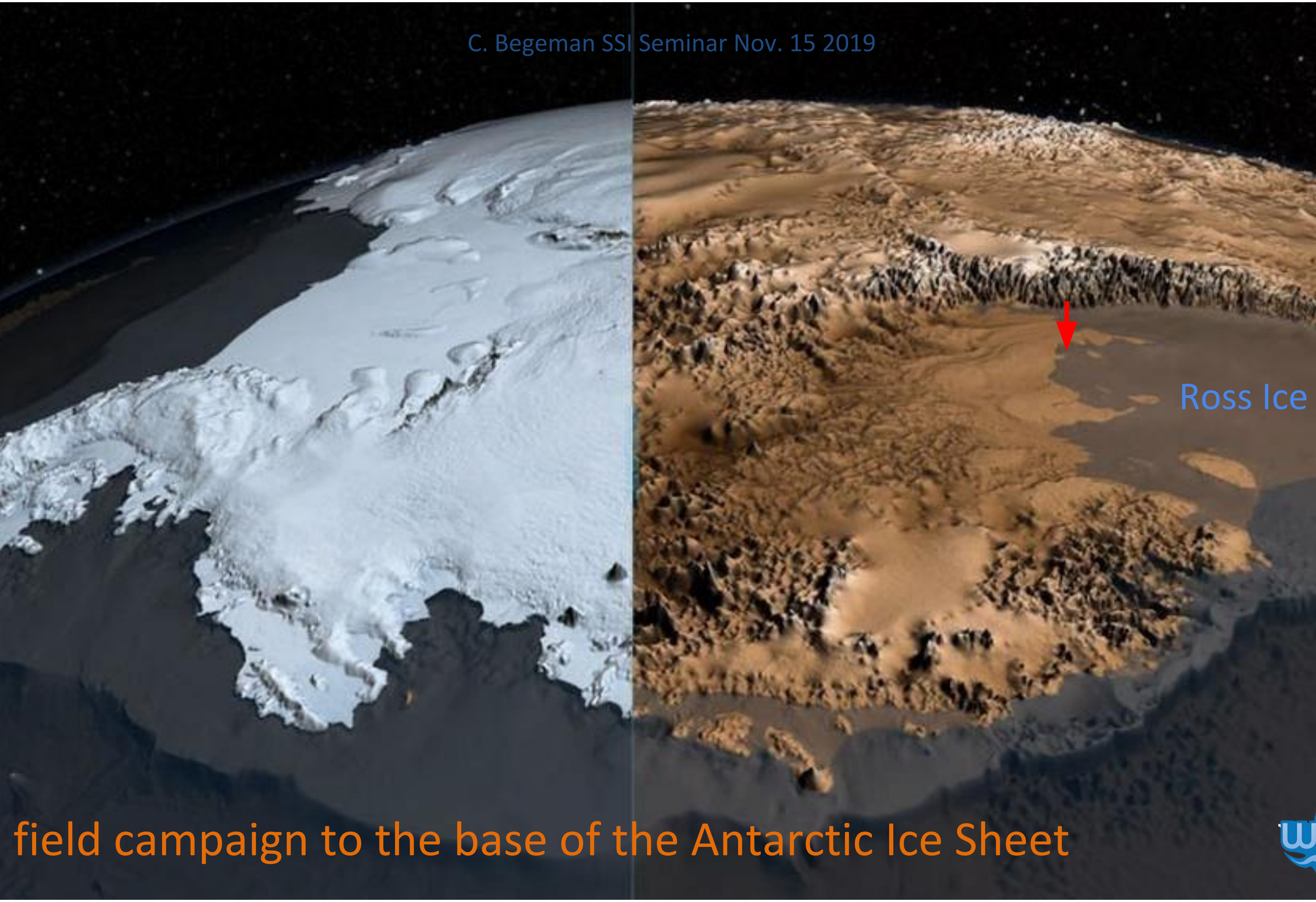

C. Begeman SSI Seminar Nov. 15 2019
Ross Ice
field campaign to the base of the Antarctic Ice Sheet


C. Begeman SSI Seminar Nov. 15 2019
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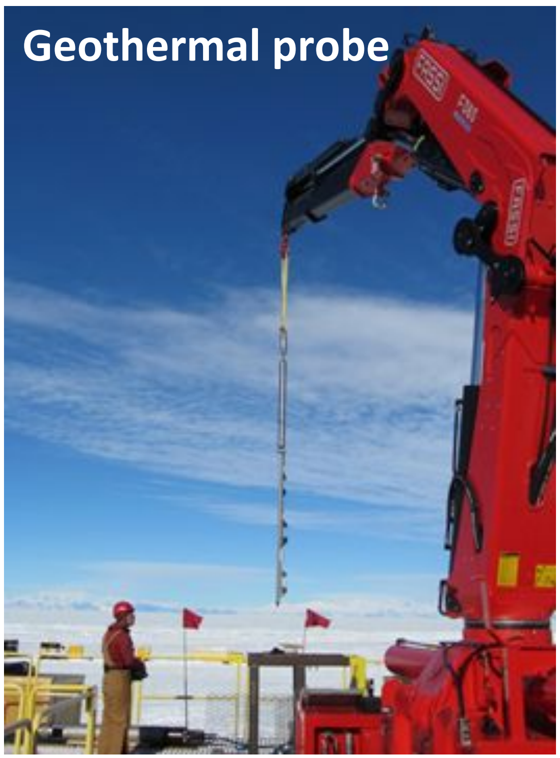
Drilling pla

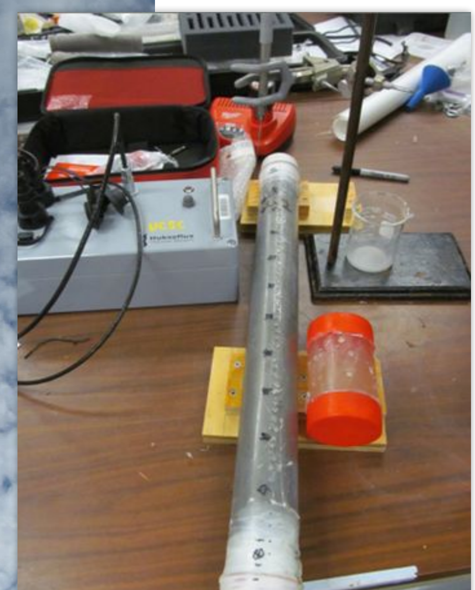
Measuring geothermal heat flux

G = Temperature gradient in sediments x Thermal conductivity of sediments = 88 ± 7 mW m^{-2}

average continental G = 6

n=2 n=40





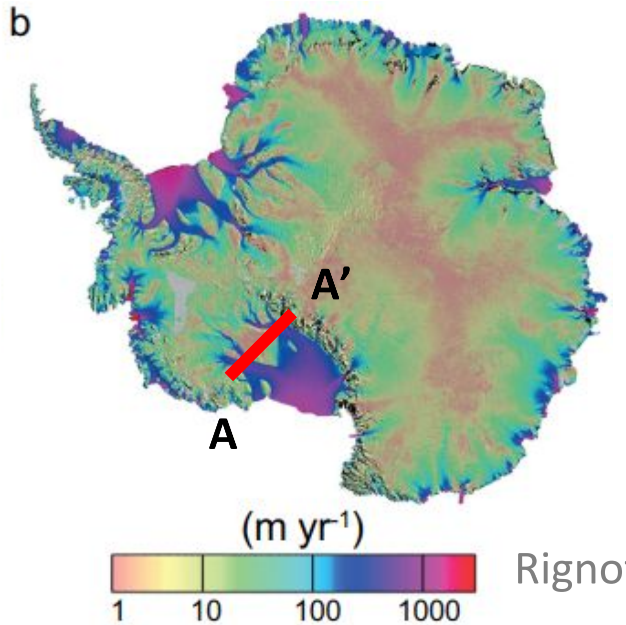
Methods: Fit temperature evolution after thermal pulse to an analytical model

Is geothermal heat important to the basal heat budget?

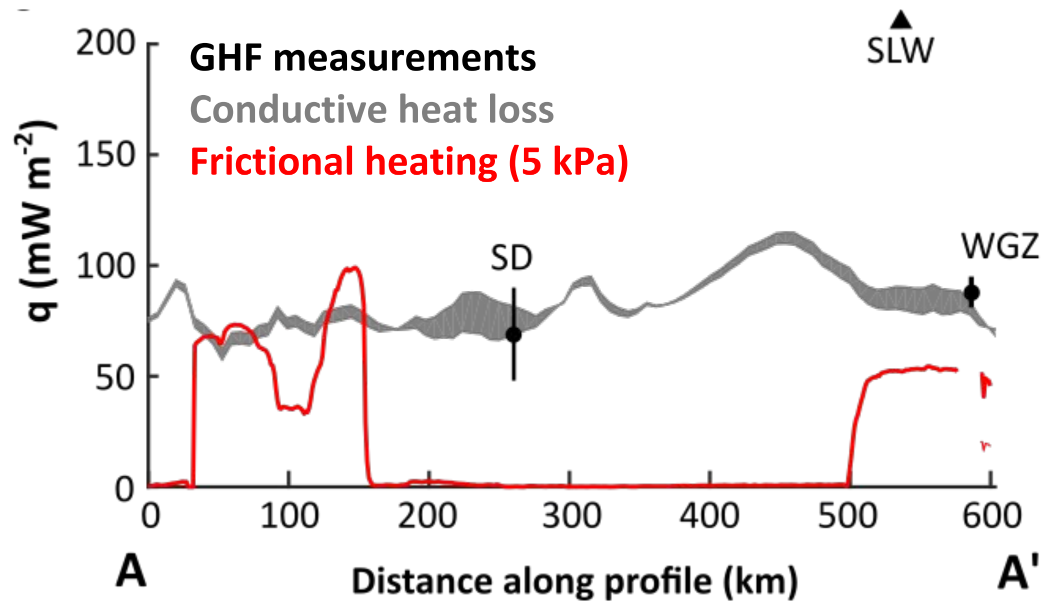
Basal melting	geothermal heat flux	frictional heat flux	conductive heat loss

$$\rho_i L m = k_s dT_s/dz + \tau_s u_i - k_i dT_i/dz$$

Ice velocity



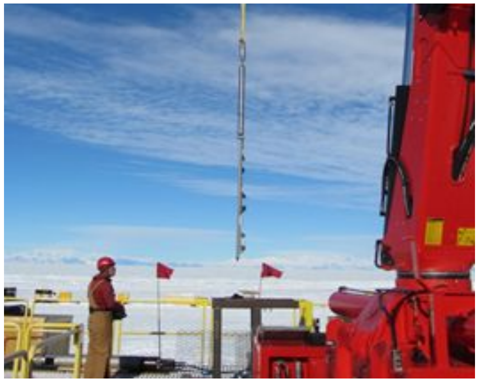
Rignot et al., 2009

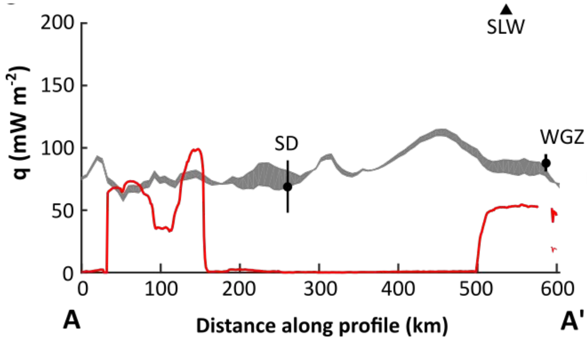


Methods:
Analytical model for thermal advection and conduction in ice and Earth's crust

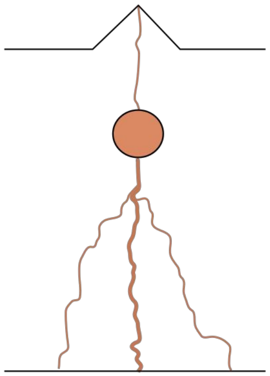
Ⓐ Progress on geothermally-driven ice melting

I measured geothermal heat flux at a new site, which will help constrain future continent-wide maps



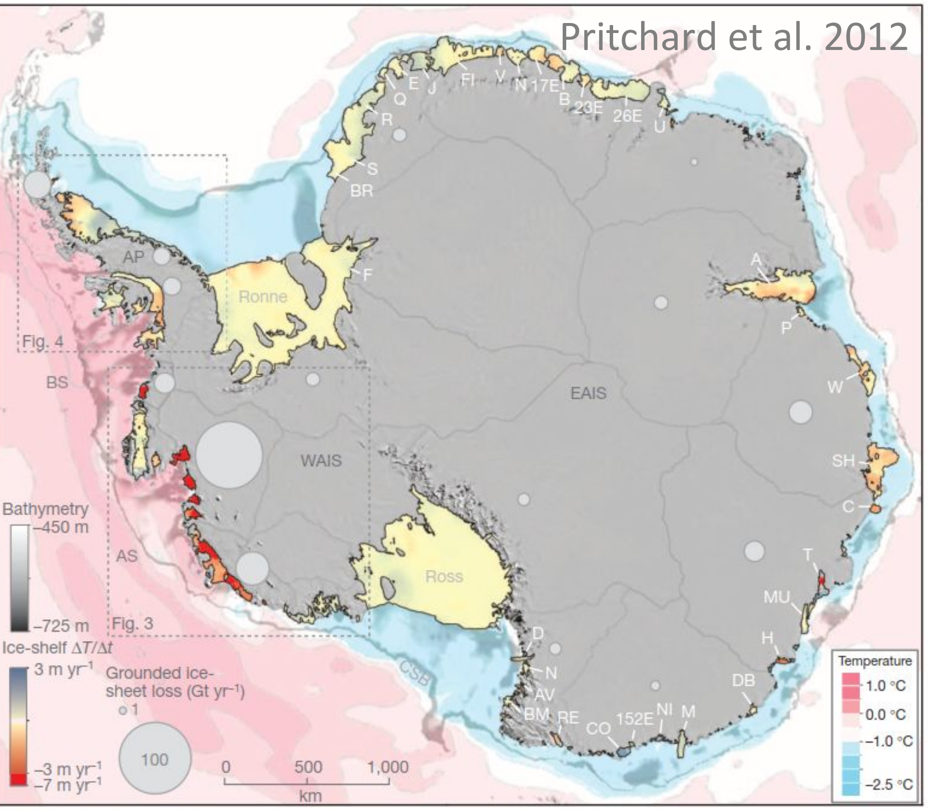


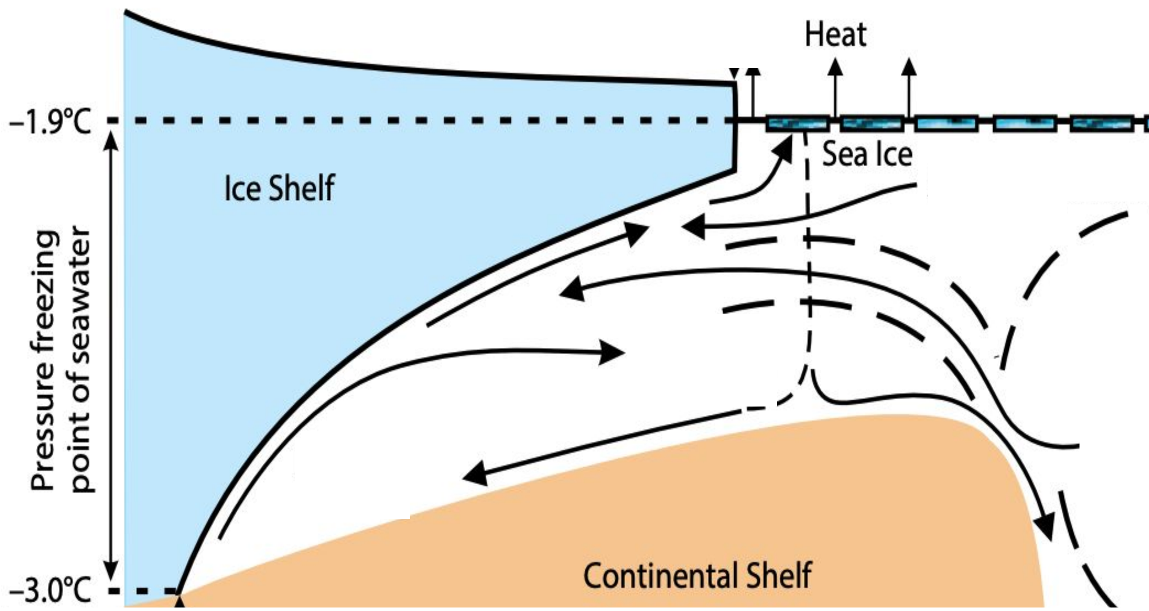
I found that geothermal heat flux is glaciologically important at this site



Magmatism can enhance ice loss in West Antarctica

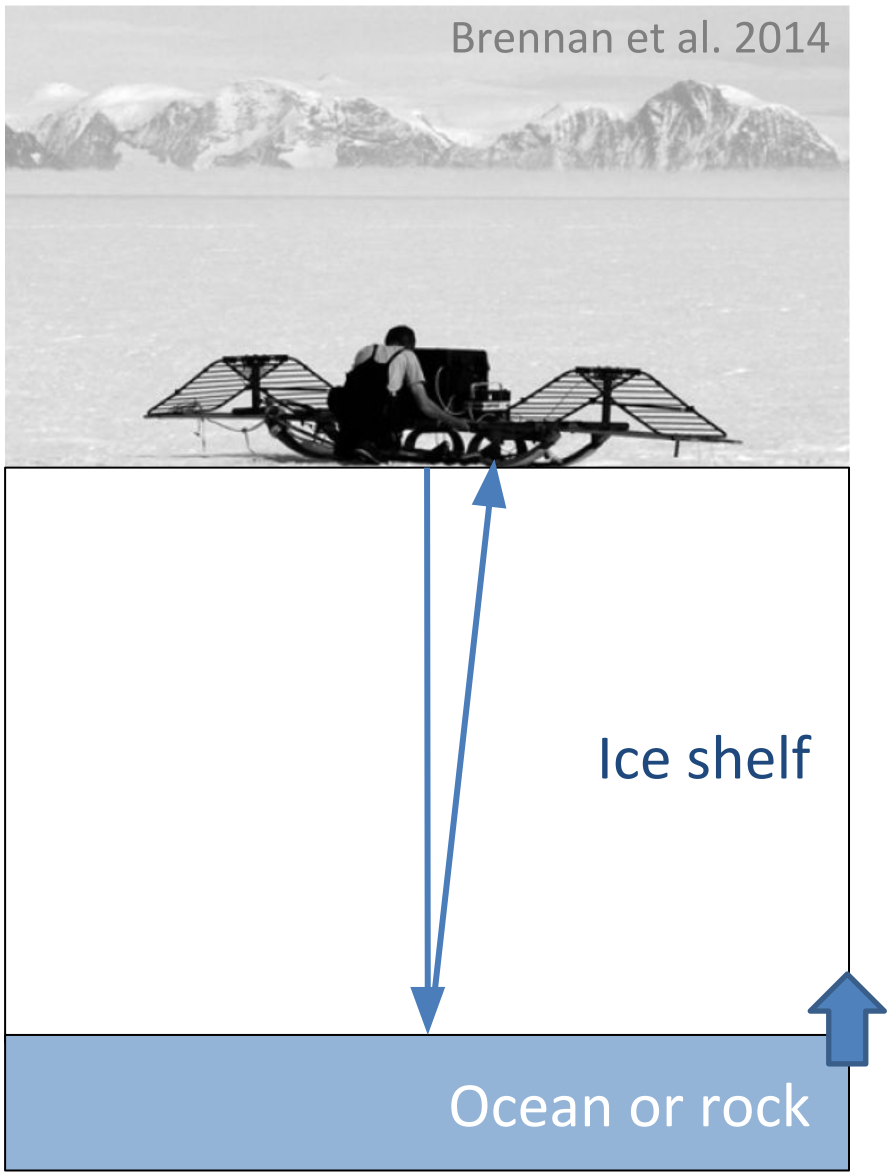
B) What is the relationship between melting and ocean conditions





DInniman et al. (2016)

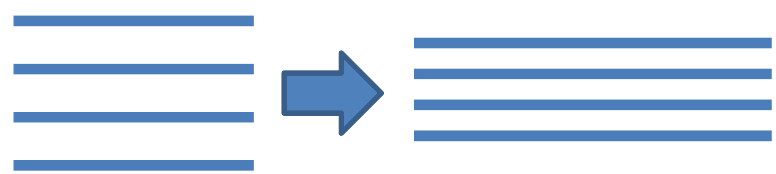
The cutting edge in ice melt measurements



Phase-sensitive FMCW radar

305 MHz center frequency,
160 MHz bandwidth

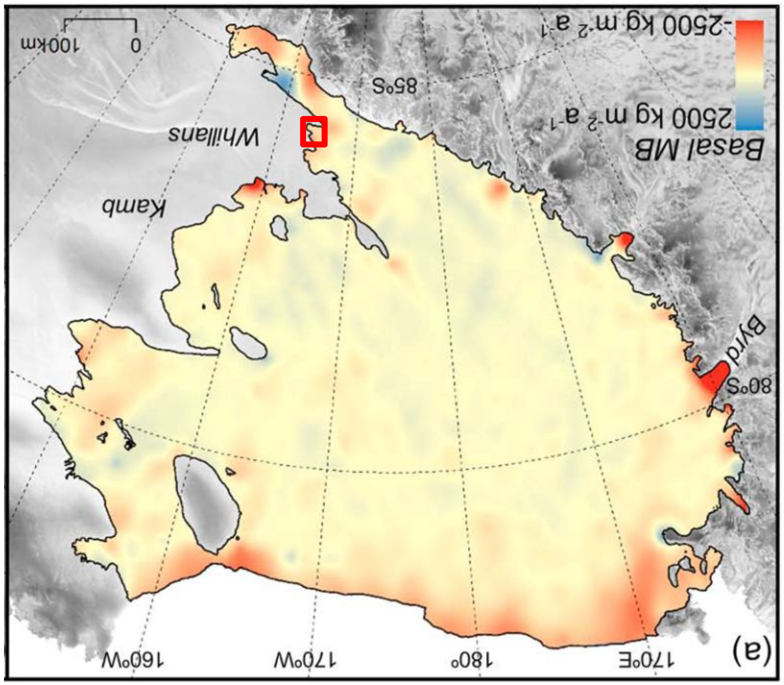
Can separate
ice-shelf thinning by stretching



from
ice-shelf thinning by melting

Spatial and temporal melt variability remains largely unexplaine

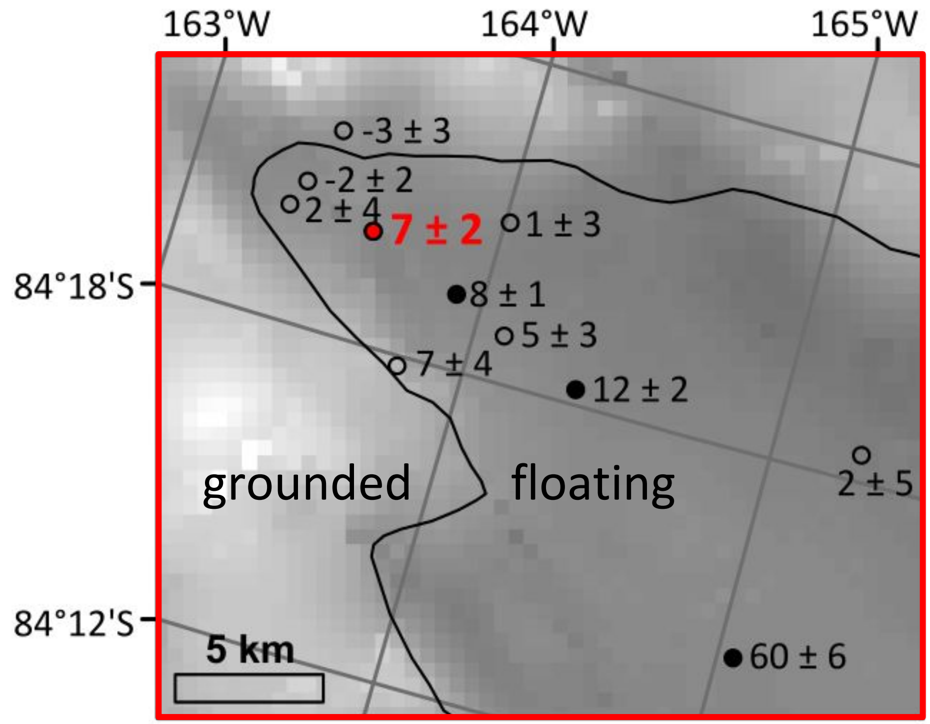
Ice-shelf average: 25 cm yr^{-1}



InSAR-derived melt rates
Moholdt et al. 2014

Melt rate
(cm yr^{-1})
270
-270

Local: < 10 cm yr^{-1}



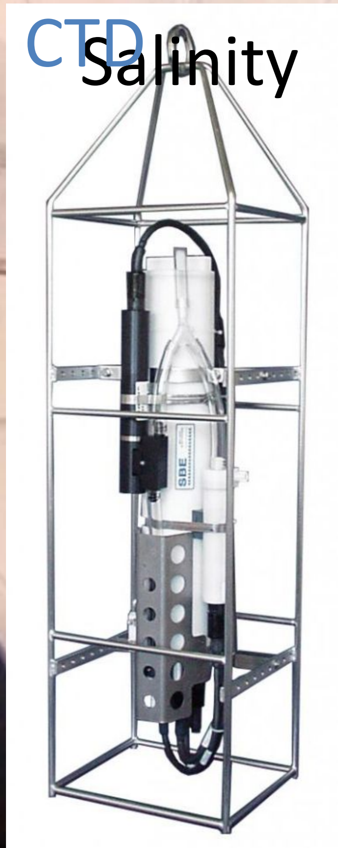
Phase-sensitive radar melt rates
Begeman et al. 2018 GRL

Oceanographic observations

Temperatur
e

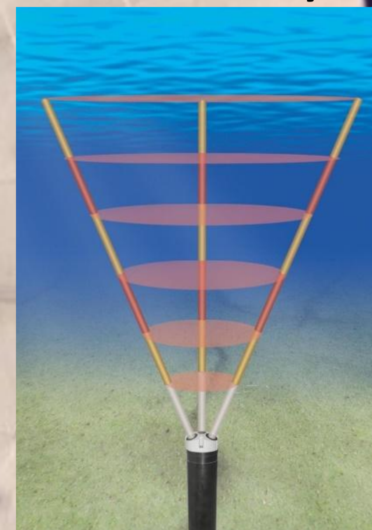
Salinity

CTD



Jill Mikucki

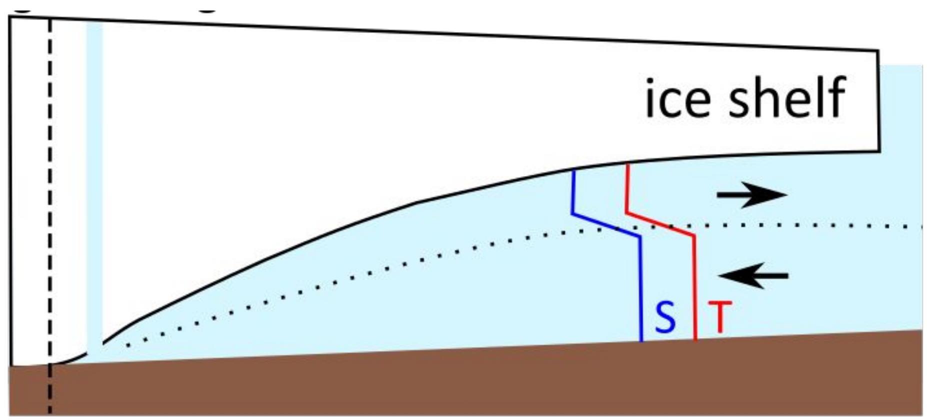
Current velocity

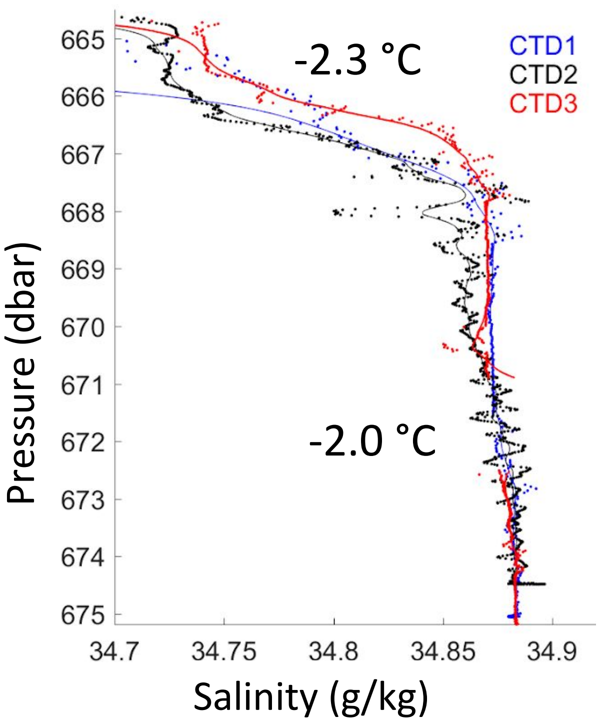


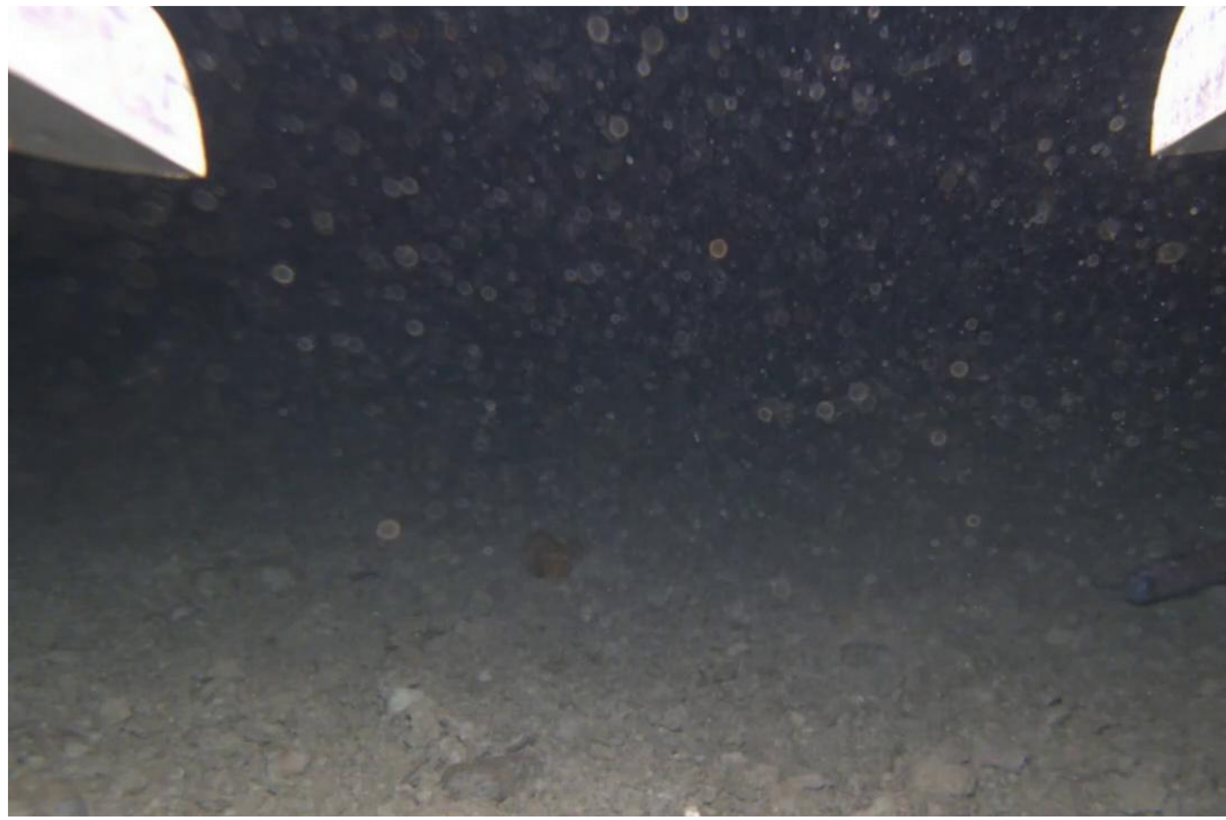
Tim Hodson

ADC

Current melt parameterization fails to accurately predict melt rates given ocean conditions







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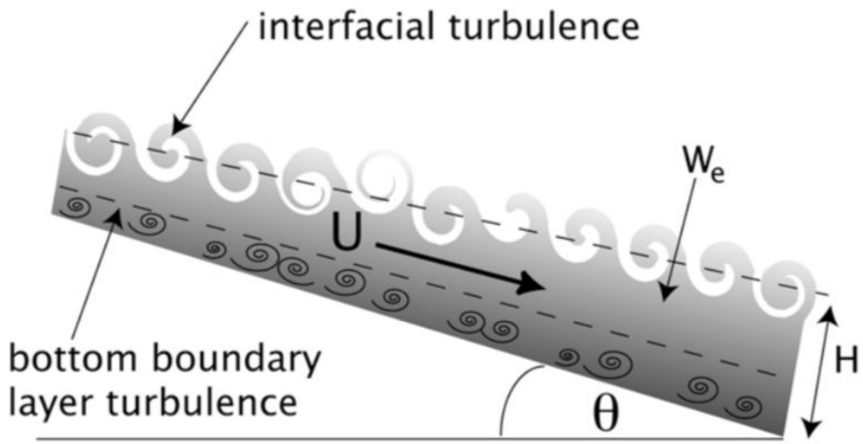
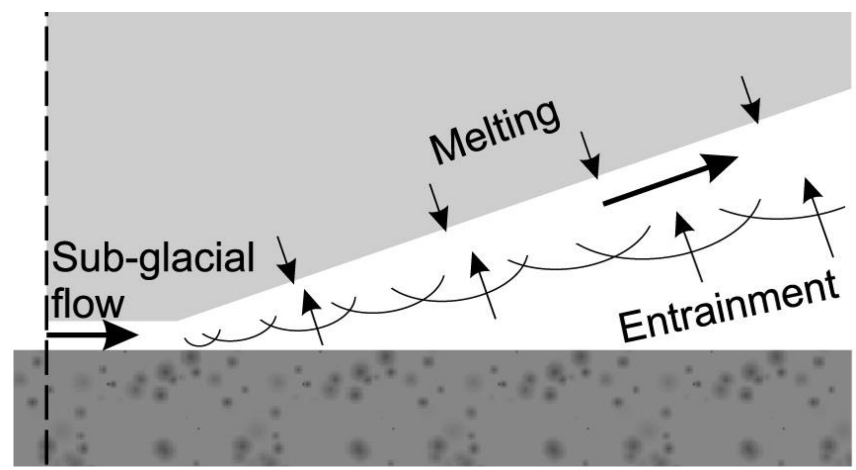
Limited understanding of vertical heat and salt transport across the ice-shelf ocean boundary layer

"plume theory" postulates that the positively buoyant ice-shelf ocean boundary layer is similar to the negatively buoyant seafloor boundary layer



Wells et al. (2010) JPO



Jenkins (2011) JPO

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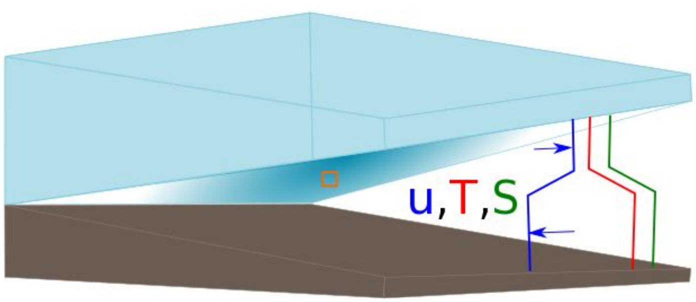
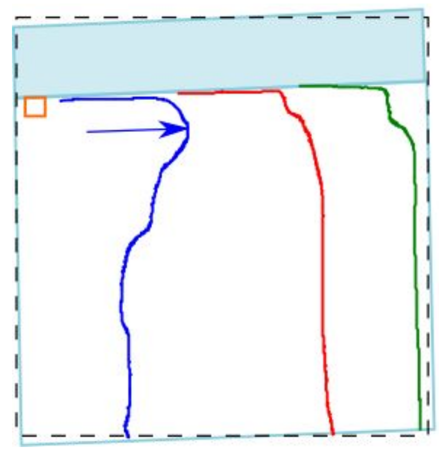
A hierarchy of ocean models

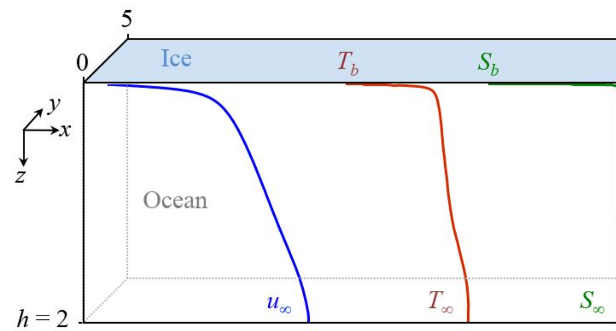
General circulation model



Large-eddy simulation



Direct numerical simula



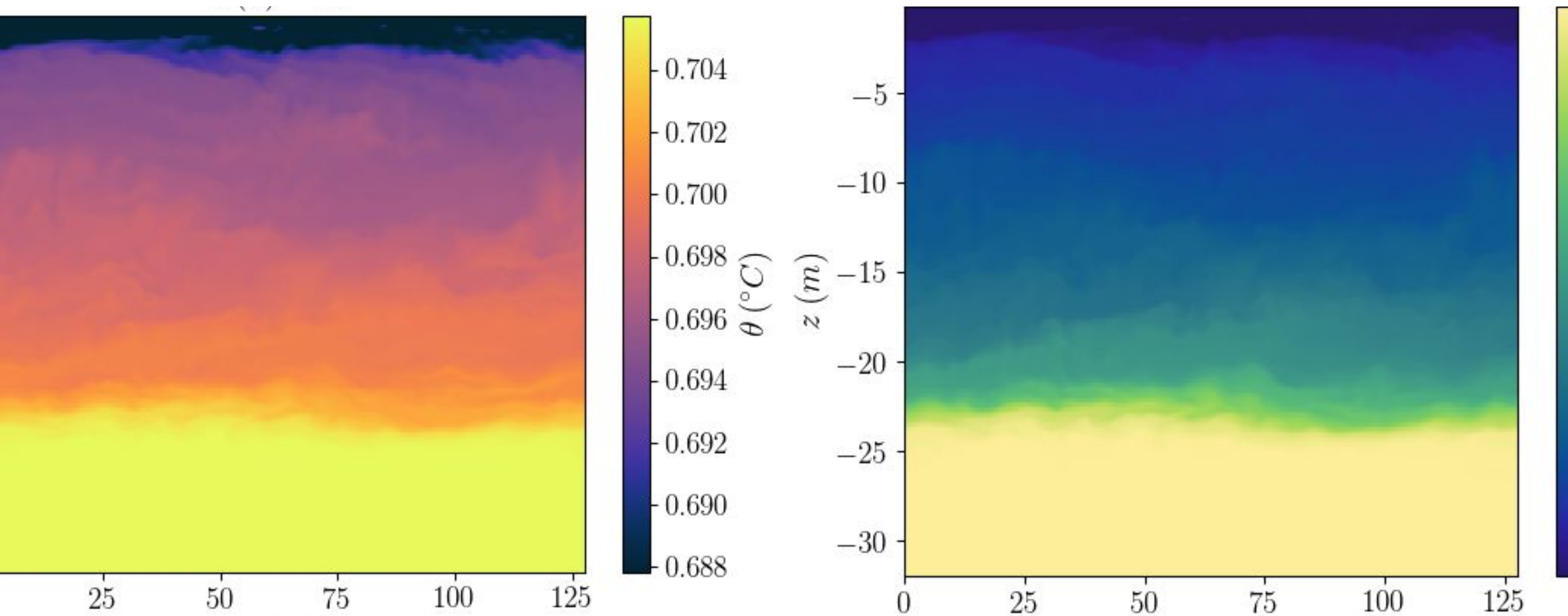
rid Δz:	>10 m	0.25 m	0.05 m
ddy viscosity:	fully parameterized	sub-grid parameterization	no parameterization

Modeling the ice-shelf ocean boundary layer

PArallelized Large-eddy Model, Leibniz Universitat Hanover

- Large-eddy models resolve the energy-containing scales of the flow and parameterize scales that are not resolved
- **Sloping surface at the top of the domain**
  - Gravity and coriolis are rotated
  - Drag formulation that accounts for stratification
- **Dynamically-melting ice**
  - Heat and salt fluxes based on sea ice observations and DNS
  - Nonlinear freezing point
- **Tidal forcing**
  - time-varying large-scale horizontal pressure gradients

Ice-shelf ocean boundary layer development in PALM



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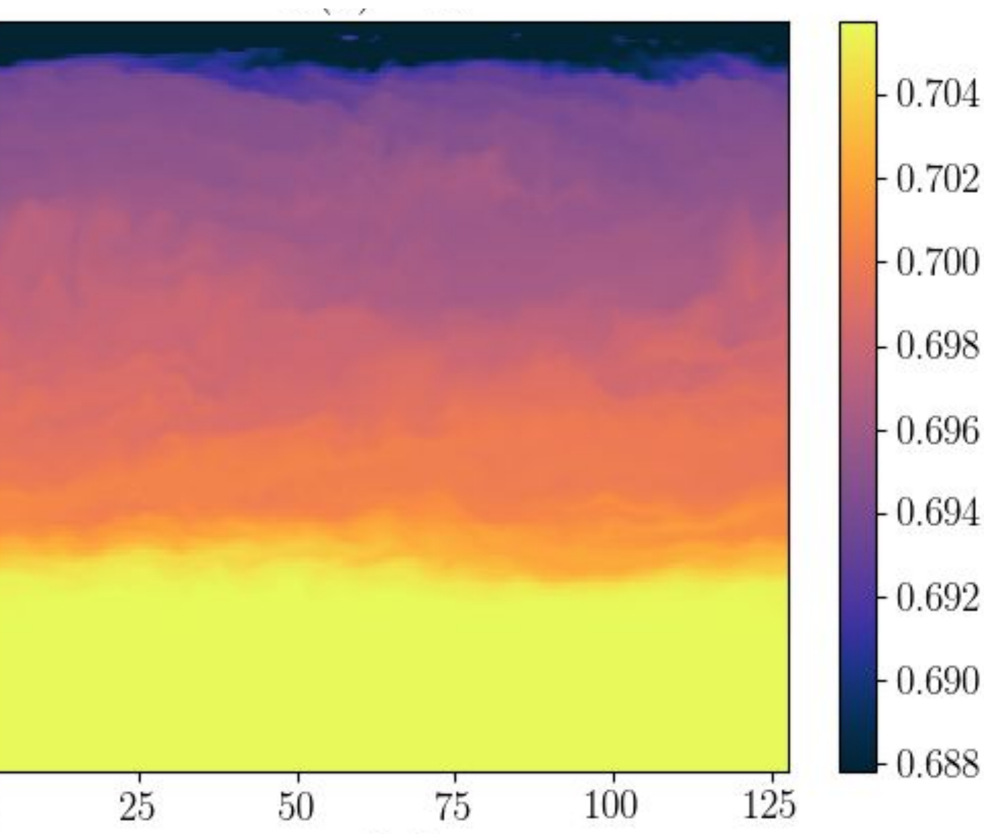
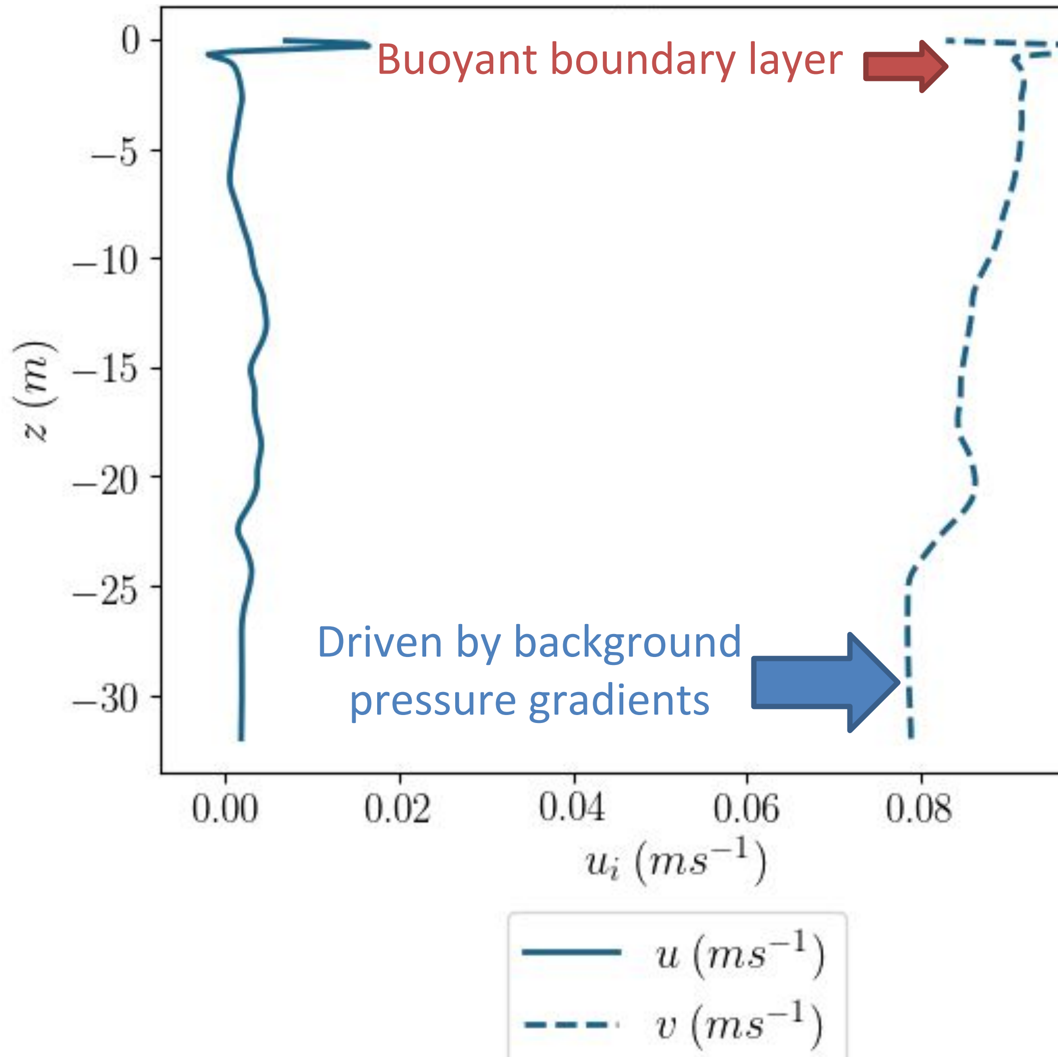
Ice-shelf ocean boundary layer development in PALM

1.5 m yr^{-1} melt rate





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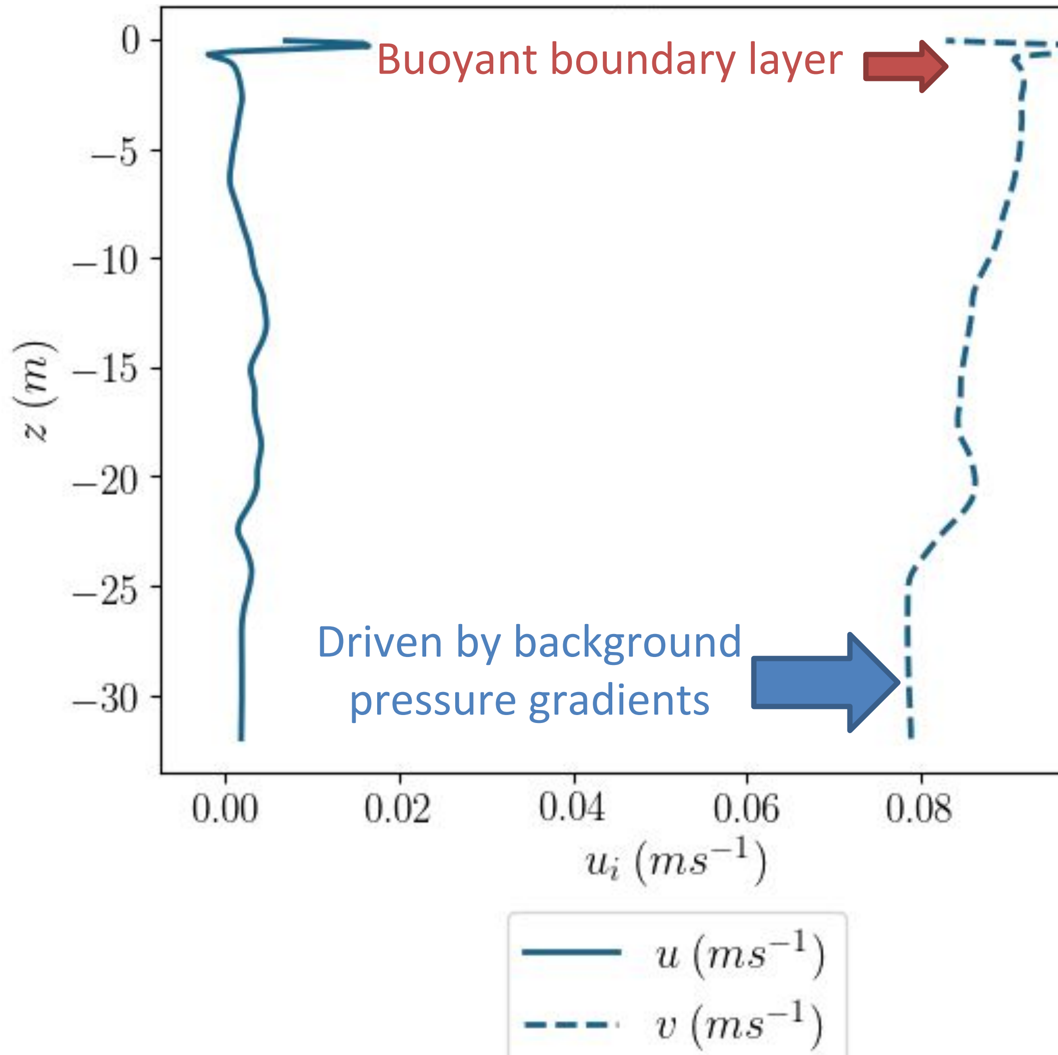
Ice-shelf ocean boundary layer development in PALM

Momentum transport across the boundary layer is heavily influenced by stable stratification



Ice-shelf ocean boundary layer development in PALM

Momentum transport across the boundary layer is heavily influenced by stable stratification

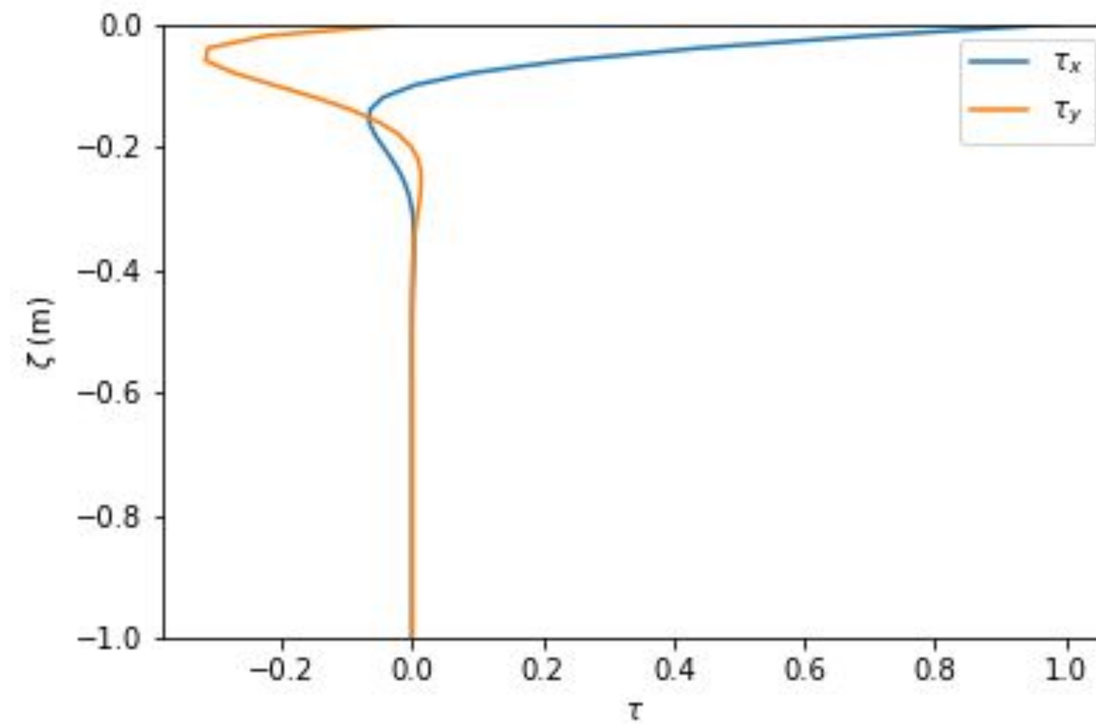
Monin-Obukhov Similarity Theory:

Scaled depth

$$\zeta = z/L_O$$

Monin-Obukhov length

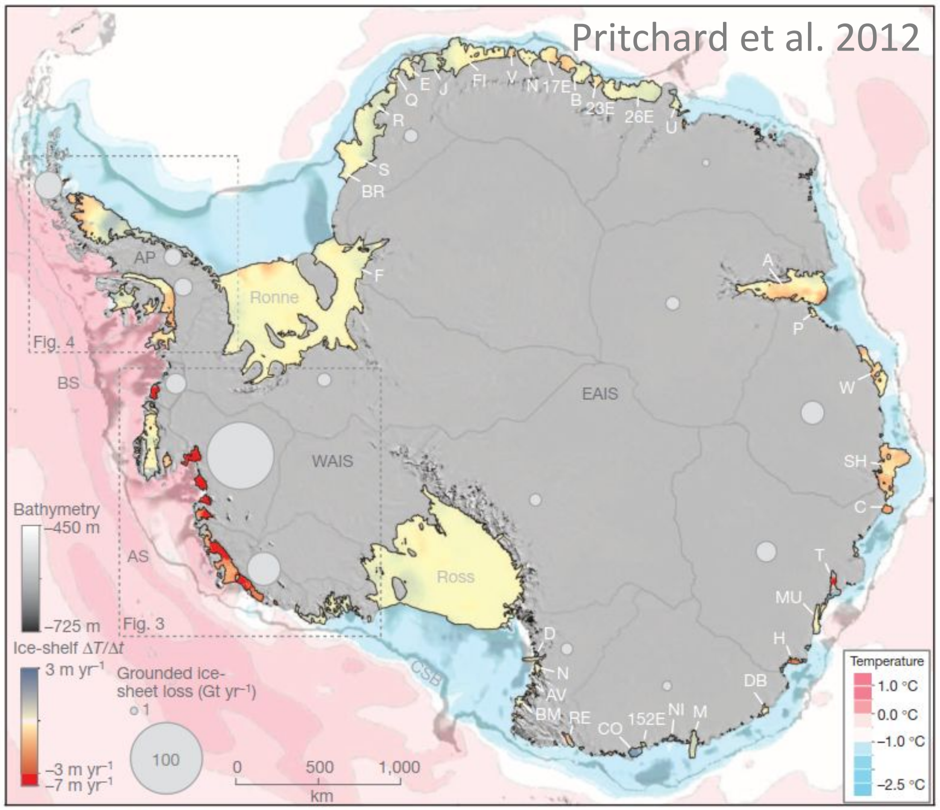
$$L_O = \frac{\rho u_*^3}{\kappa F_B}$$



Stress or vertical momentum flux

What is the relationship between melt rates and ocean condition

Melt rate = f (temperature, salinity, pressure, velocity, slope, basal roughness)

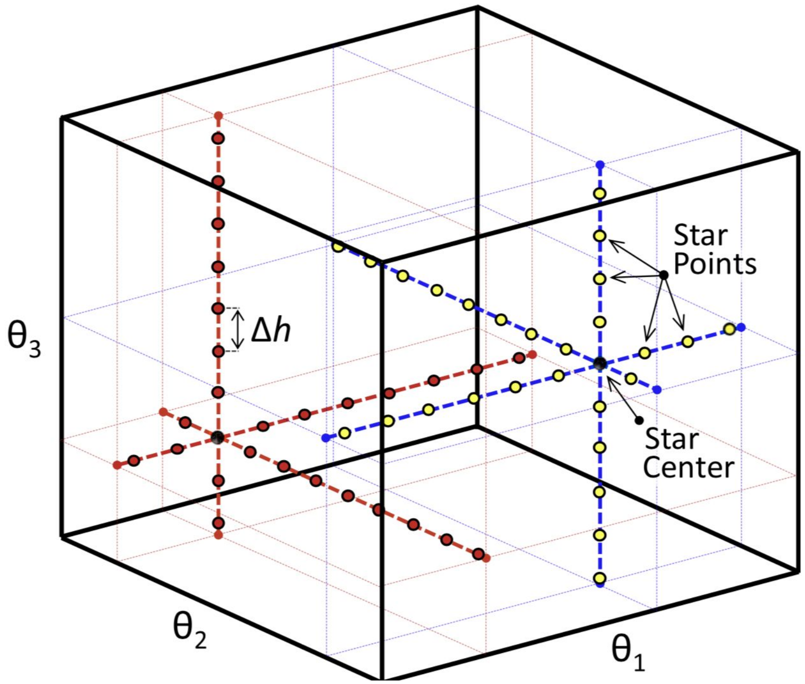


k degrees of freedom

- k is at least 7, not counting tidal frequencies

What is the relationship between melt rates and ocean condition

Melt rate = f (temperature, salinity, pressure, velocity, slope, basal roughness)



k degrees of freedom

- k is at least 7, not counting tidal frequencies

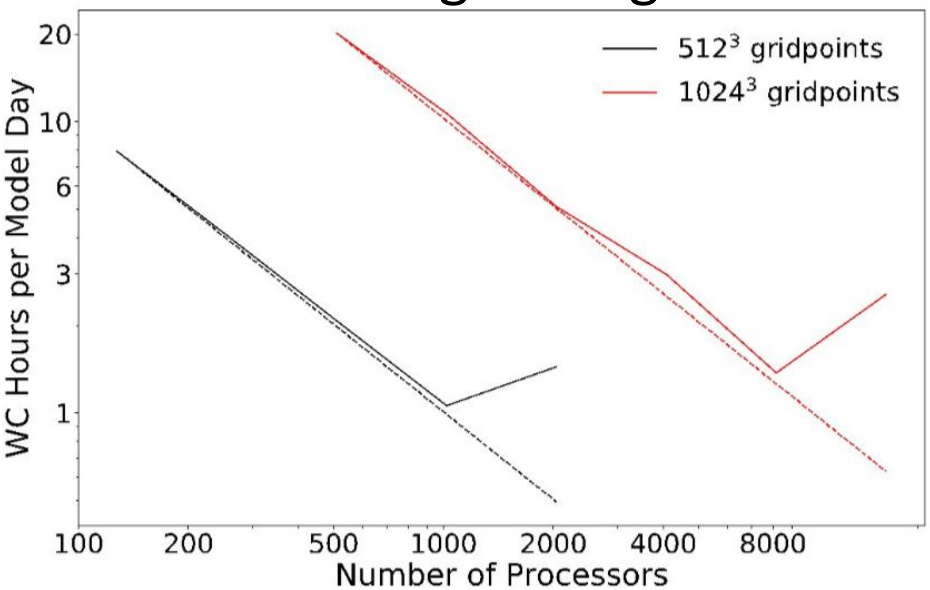
Sensitivity analysis:

n samples of k-dimensional space

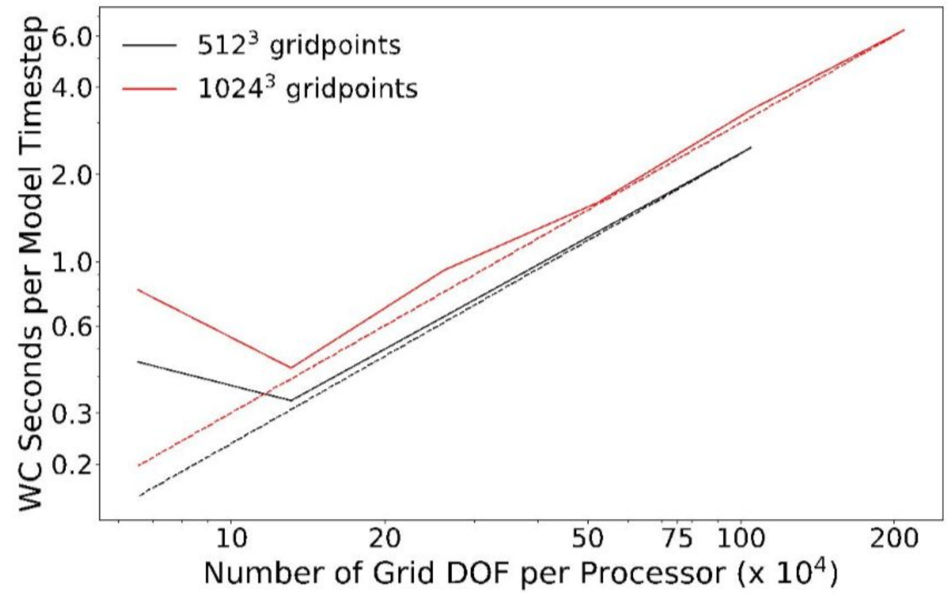
- Variance-based: n(10k+1)
- Derivative-based: n(k+1)

The computational cost of large-eddy simulations

Strong scaling



Weak scaling



~30K core-hours per simulation

Allocated 6.6M core-hours on LANL machines

~100 simulations to constrain new melt parameterization

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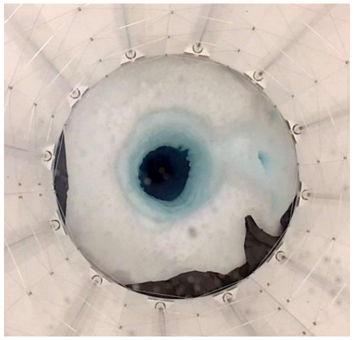
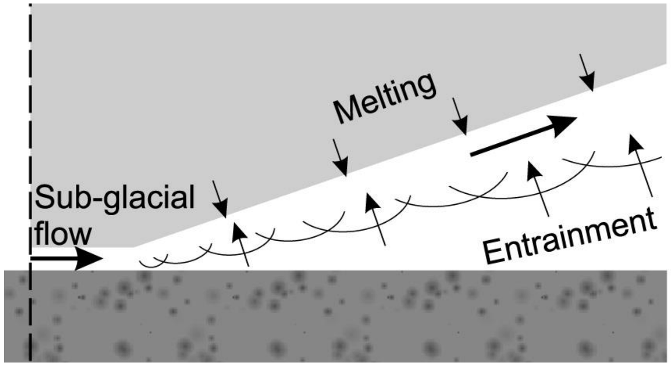
Ⓑ Progress on the dynamics of ice-shelf melting

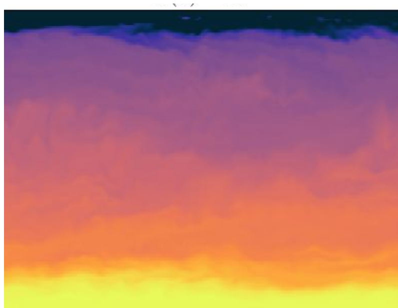
Observations of both ice-shelf melting and ocean conditions reveal that our existing melt parameterization is inaccurate





I developed a large-eddy simulation code to capture the unique configuration and forcing for an ice-shelf ocean boundary layer

I am running a suite of simulations to inform a new melt parameterization for global ocean models



Thank you

Personal website **carolynbegeman.weebly.com**

DOE Earth System Model website **e3sm.org**

Begeman, C., et al. 2018. Ocean stratification reduces melt rates at the grounding zone of the Ross Ice Shelf. Journal of Geophysical Research, Oceans.

Begeman, C., Tulaczyk, S., Fisher, A. 2017. Elevated and spatially geothermal fl below the West Antarctic Ice Sheet. Geophysical Research Letters.

Begeman, C. et al. 2019. Ice-shelf ocean boundary layer dynamics from large-ed simulations. AGU Fall Meeting.