Modeling the drift and decay of giant tabular icebergs

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CESM Workshop

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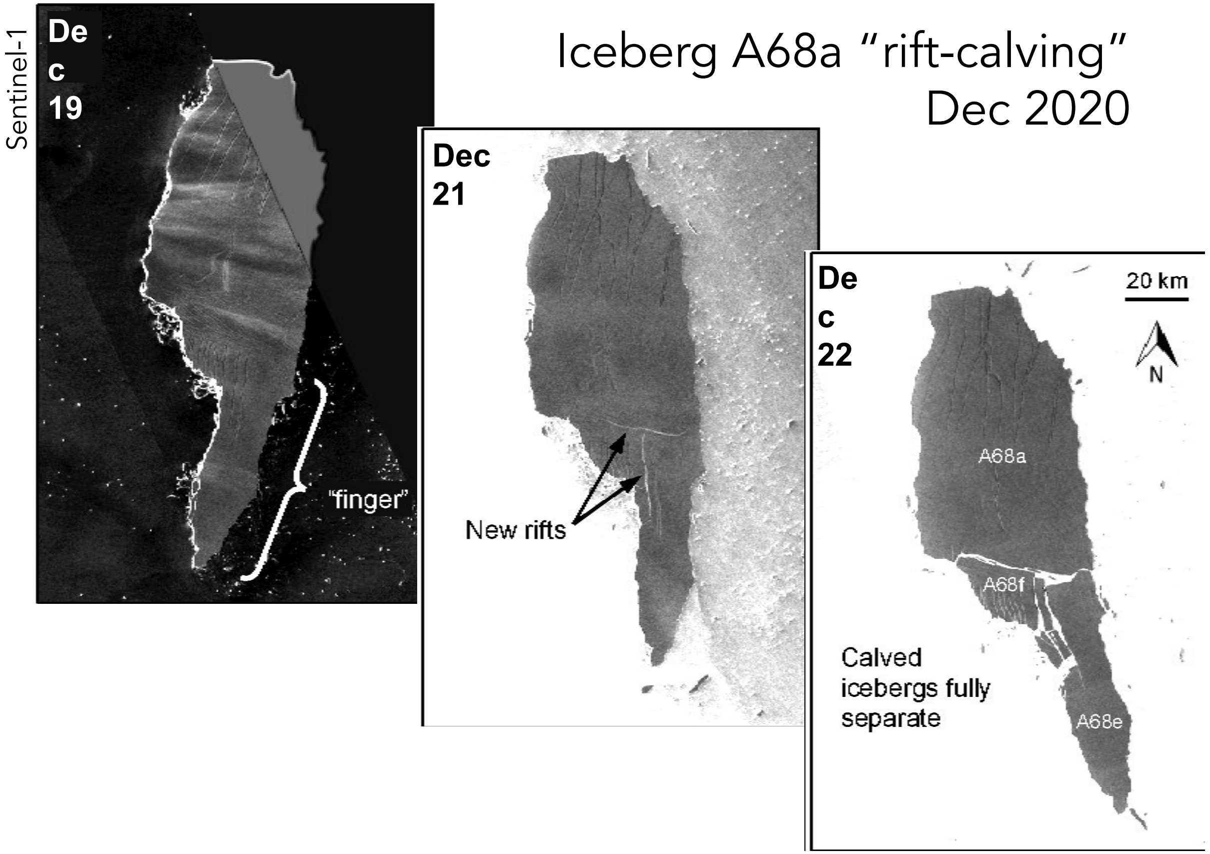
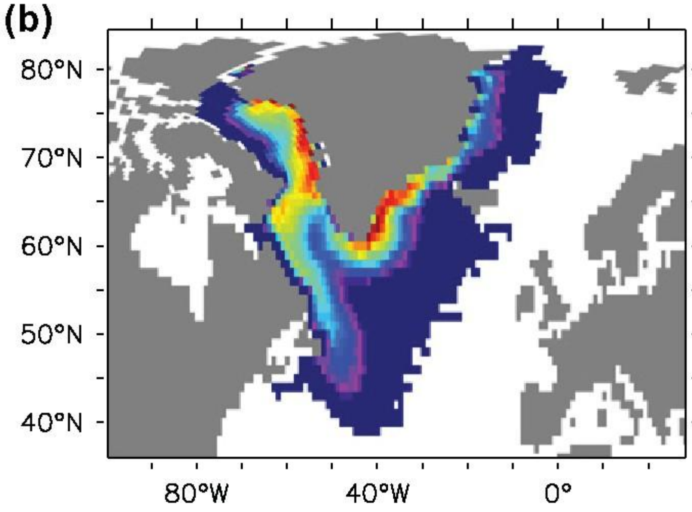


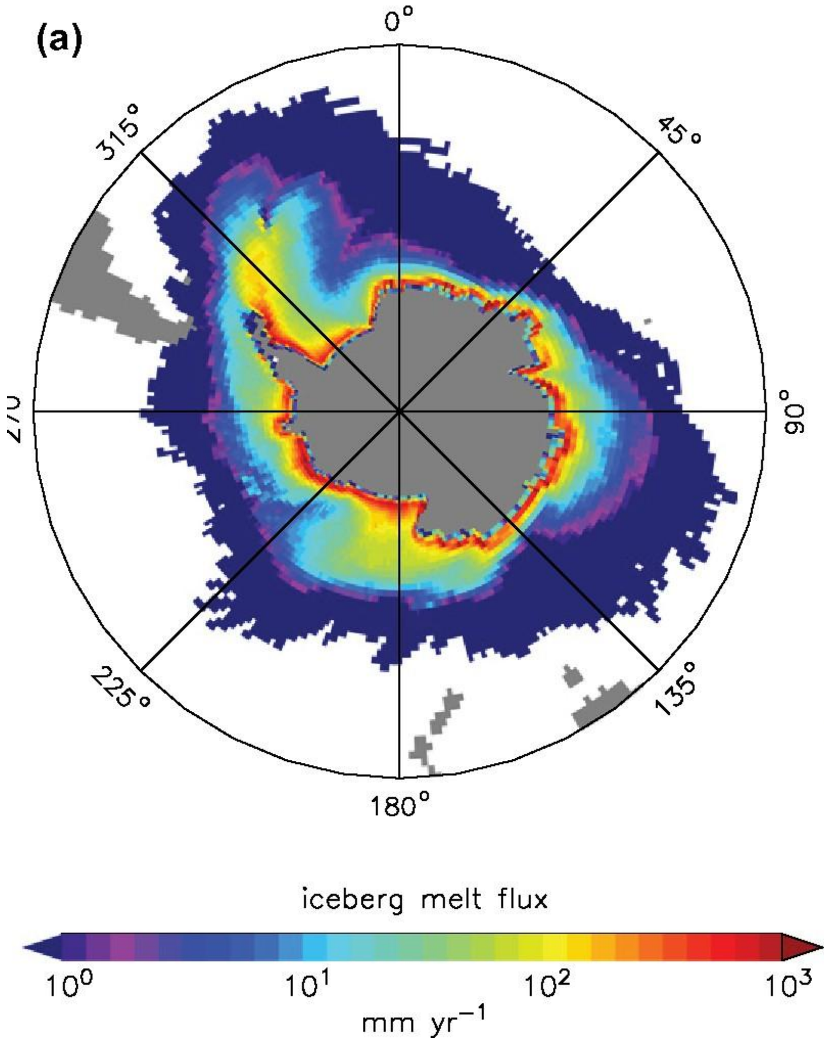
1) Develop methods to represent large tabular icebergs and their breakup within Earth system models
2) How does breakup affect where icebergs drift and deposit meltwater into the ocean?
3) What caused the Dec 2020 breakup of iceberg A68a?

Icebergs influence climate

- Icebergs comprise about half of the freshwater flux from ice sheets to the ocean

- Their meltwater can affect:
  - Sea-ice formation
  - Ocean circulation
  - Biological primary productivity

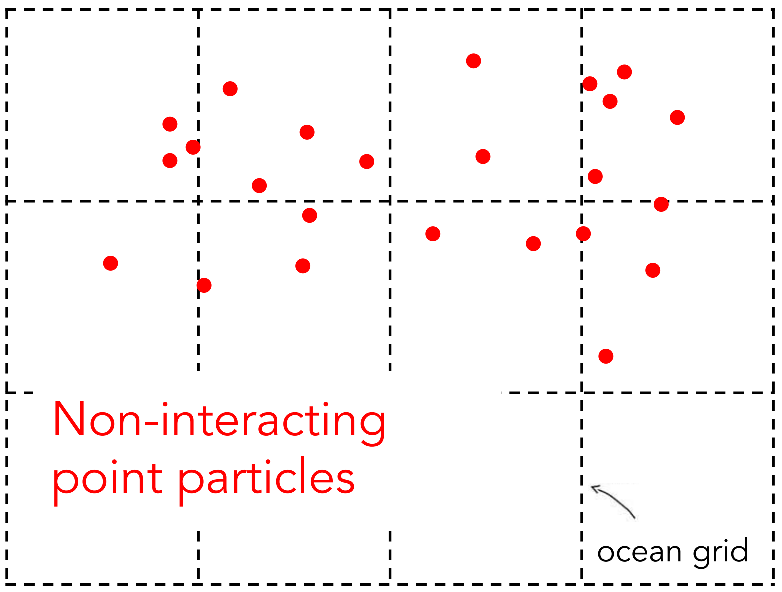




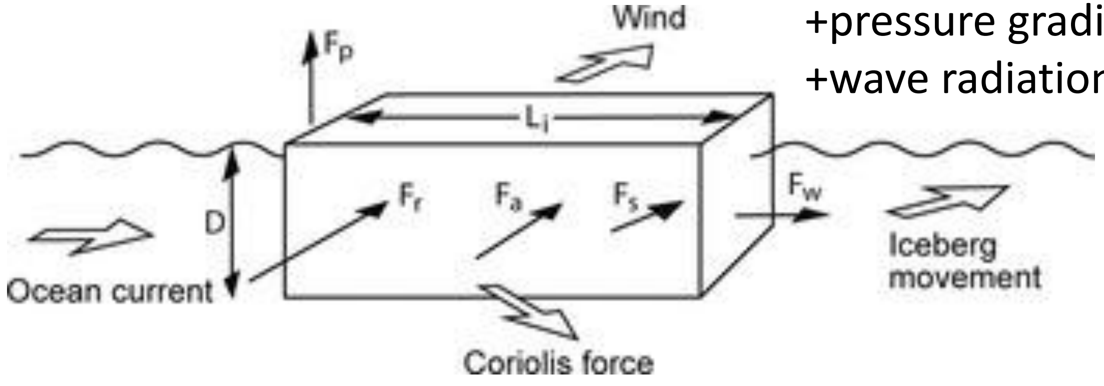
Martin and Adcroft (2010)

Icebergs in GFDL climate models are modeled as Lagrangian point particles

Initialization (“calving”):
Convert frozen freshwater flux from land to ocean into iceberg particles with various sizes

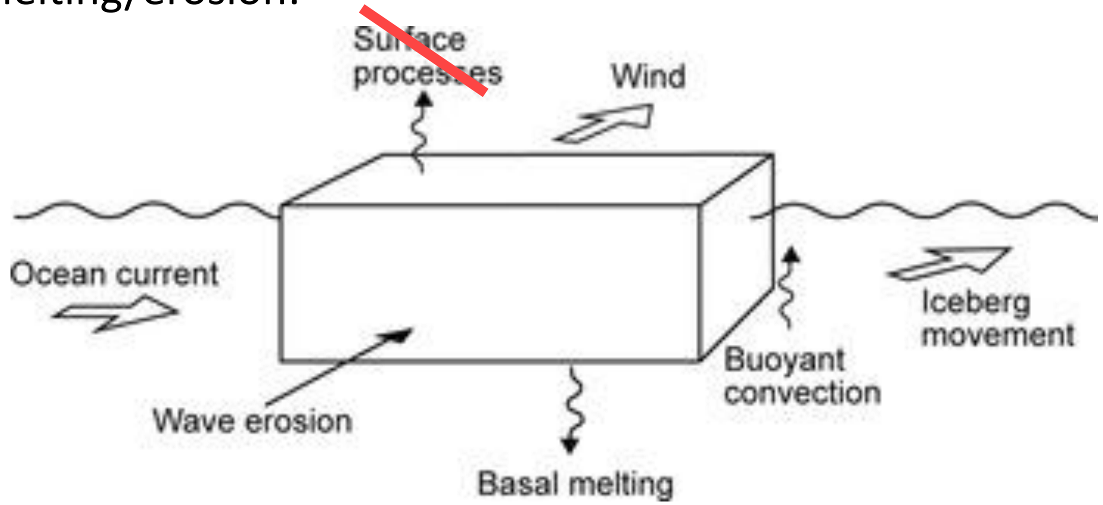


Environmental forces:



+sea ice drag
+pressure gradient
+wave radiation

Melting/erosion:

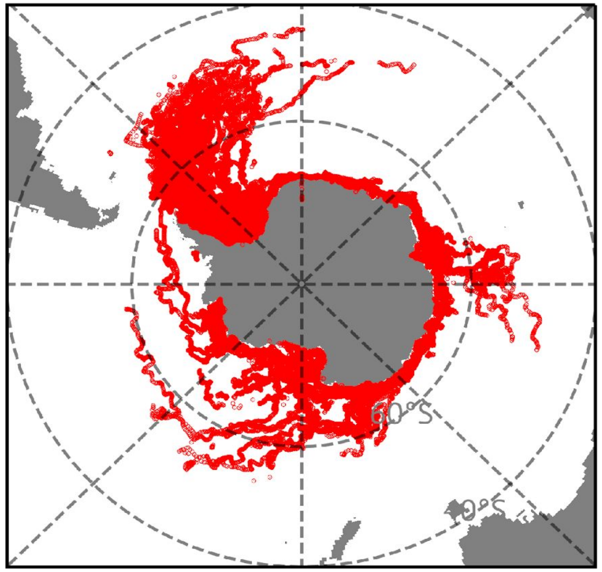


Bigg, 2016

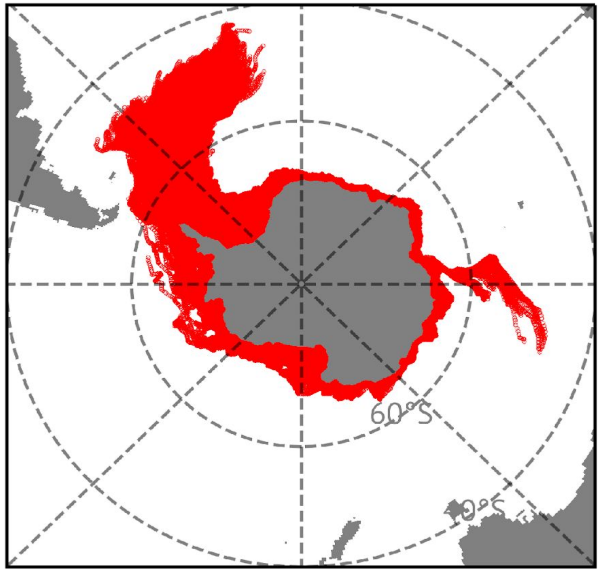
Iceberg size dictates where icebergs drift and deposit freshwater into the ocean

- Large bergs drift farther
- Giant tabular icebergs with areas > 100 km^2 represent ~90% of Antarctic iceberg volume.

Observed (NIC)
(areas 5 – 11000 km^2)

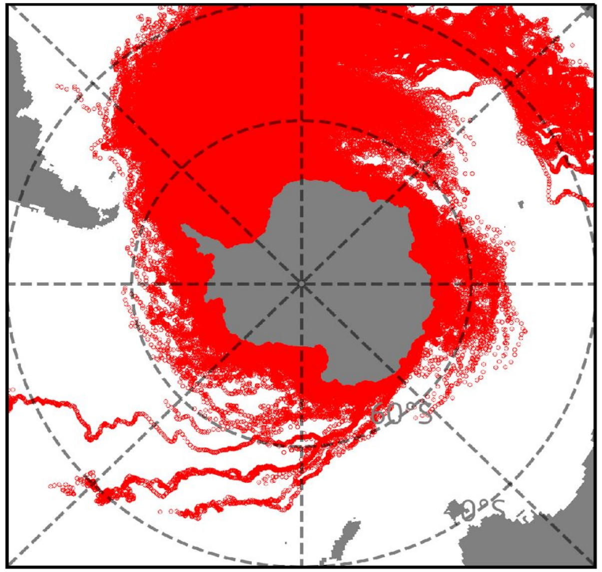


Modeled: GFDL default
(berg areas 0.5-3.5 km^2)



(top 4 mass classes)

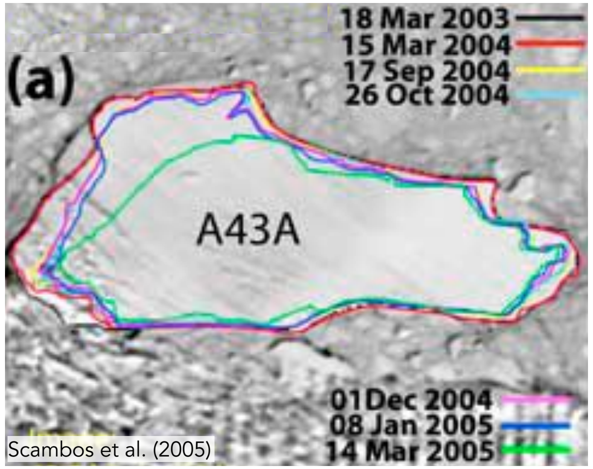
Modeled: large iceberg size distribution
(berg areas 5 –1000 km^2):

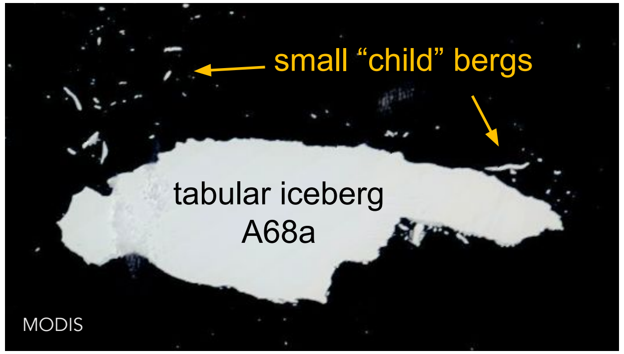


(bergs with areas > 5 km^2)

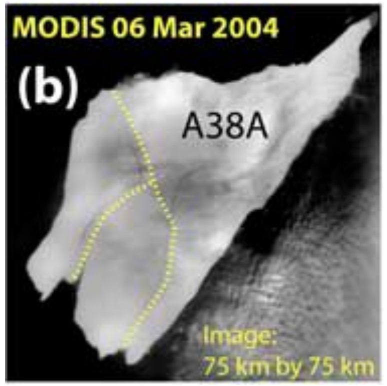
Can we represent iceberg breakup in climate models?

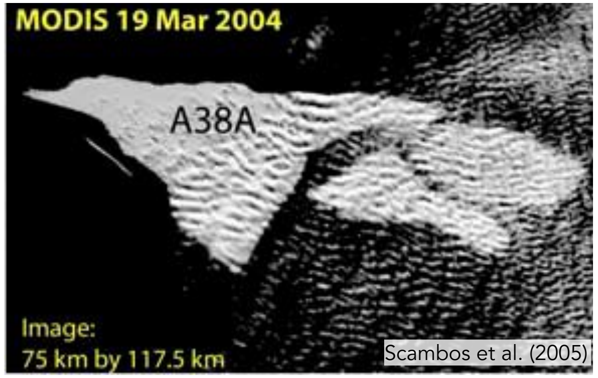
Study 1:
Footloose mechanism



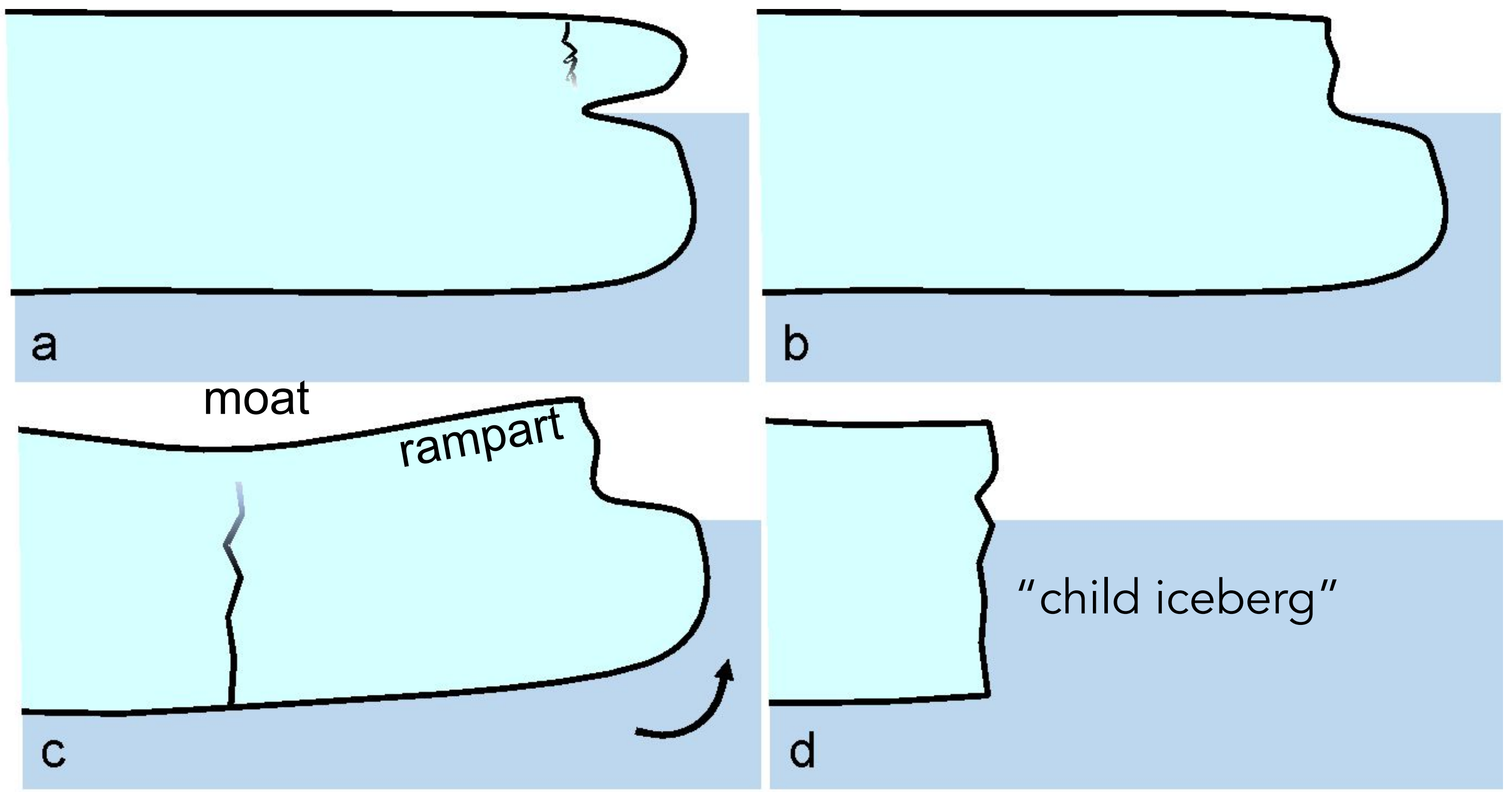


Study 2: Rift calving
(and a new modeling framework)





Study 1: The footloose mechanism

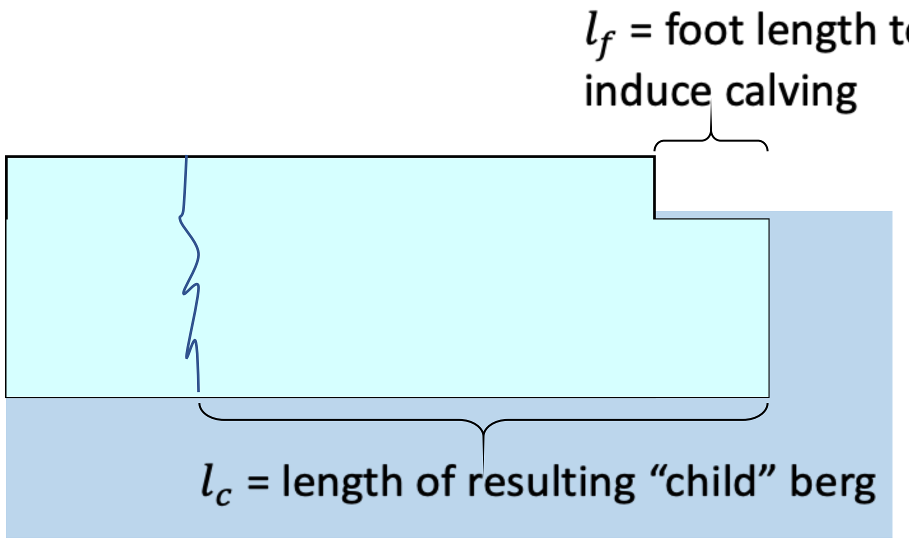


How will parameterizing the footloose mechanism change the modeled distribution of large icebergs and their meltwater?

Parameterizing the footloose mechanism

We track foot size with empirical models for erosion and melt

Elastic beam theory determines:



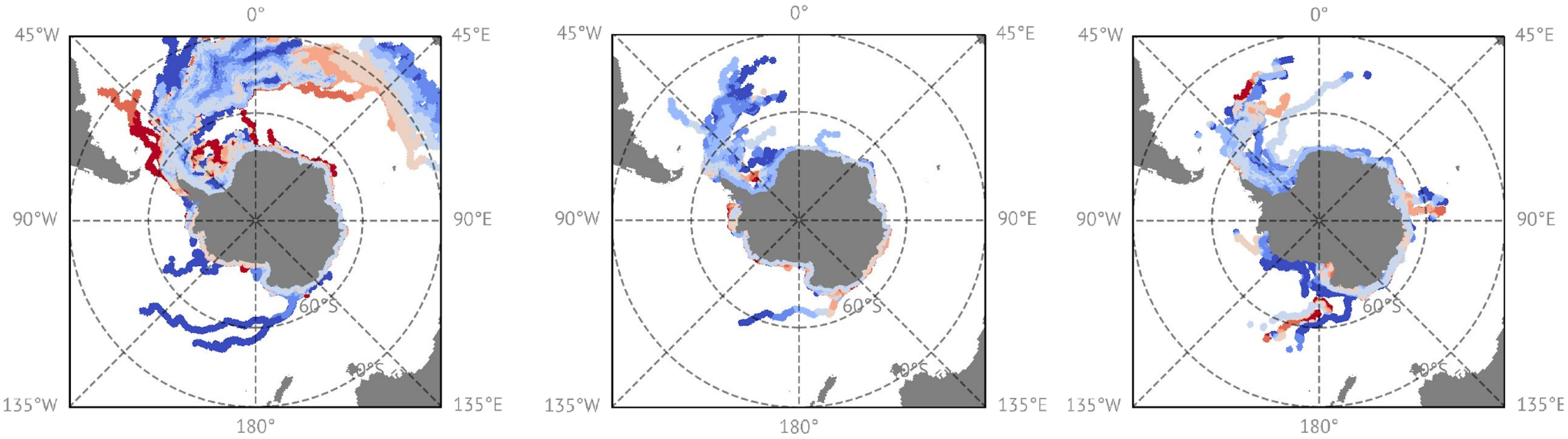
- We will vary ice stiffness and yield stress, which affects l_f and l_c
- Overall footloose decay rate is determined by l_c / l_f

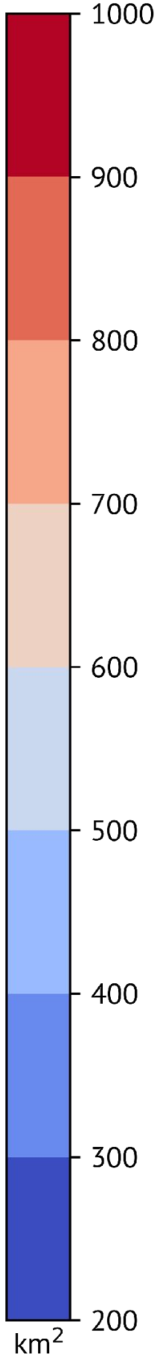
60 year simulation of large tabular icebergs with footloose

- Coupled with ocean (MOM6) and sea-ice (SIS2)
- JRA-55 for runoff and atmospheric forcing
- Max iceberg size is 1000 km^2

Average area (km^2) of large icebergs (areas 200-1000 km^2) that drift within 100 km of a grid point

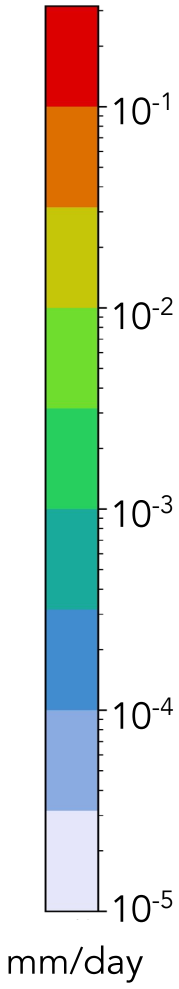
Without footloose | With footloose | Observed (National Ice Center)



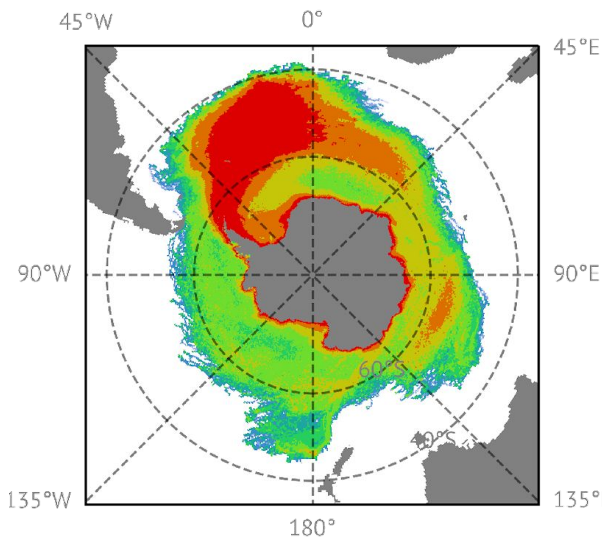


With the footloose parameterization, we can reasonably simulate the drift and decay of icebergs with areas ≤ 1000 km^2

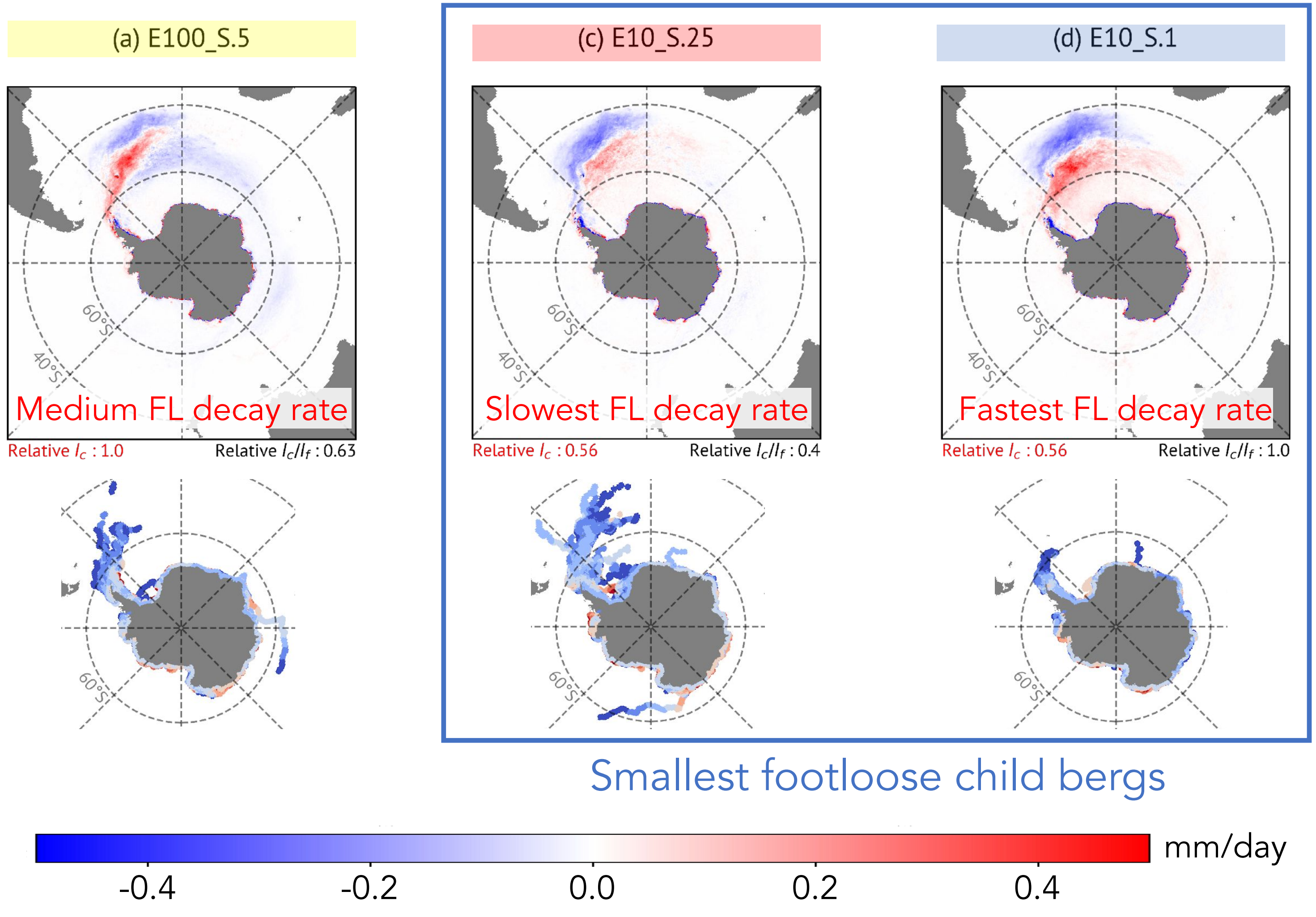
60 year simulation of large tabular icebergs with footloose



Average melt flux: original small iceberg distribution (areas ≤ 3.5 km^2):



Average melt flux anomalies compared to original small-berg simulation



- Footloose rate determines where child bergs are calved
- Smaller child bergs spread more widely from the coast due to wind

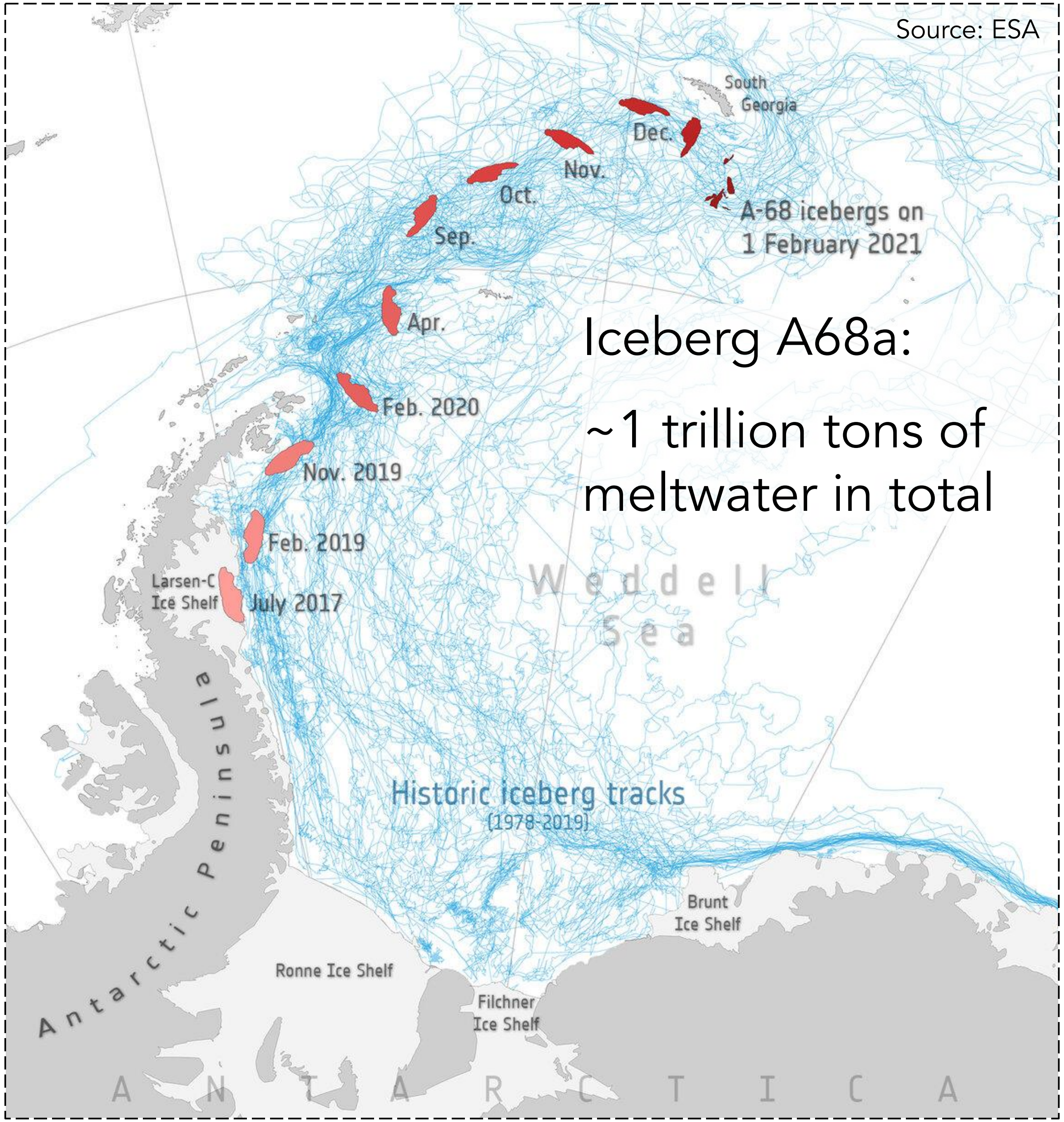
Huth et al (2022). Parameterizing tabular-iceberg decay in an ocean model. *JAMES.*

Study 2: Rift calving

(and a new iceberg modeling framework)

Goals

- Develop a new iceberg component that represents:
  - The true shape and size of all icebergs, including those with areas > 1000 km^2
  - Internal iceberg stress
- Can we simulate observed drift and breakup?
- What caused the rift-calving of iceberg A68a?

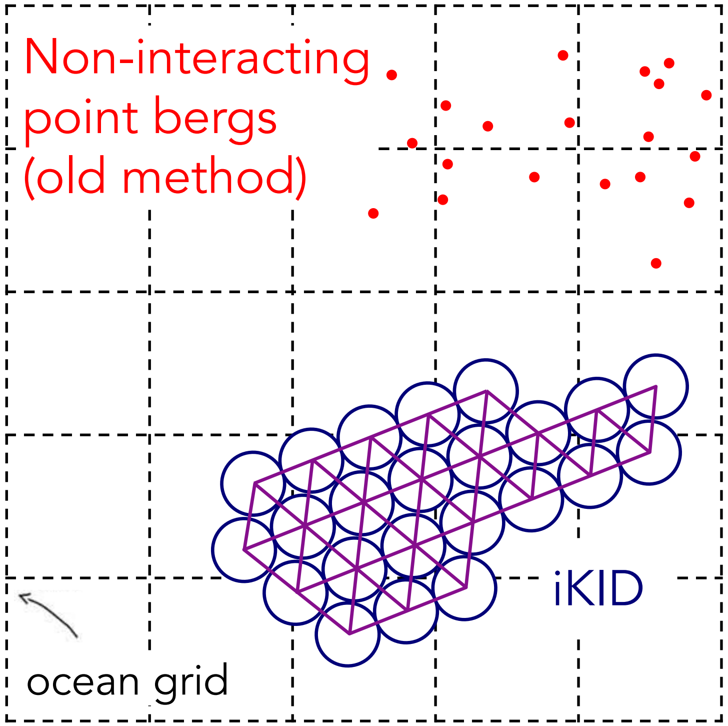


Source: ESA

Iceberg A68a:

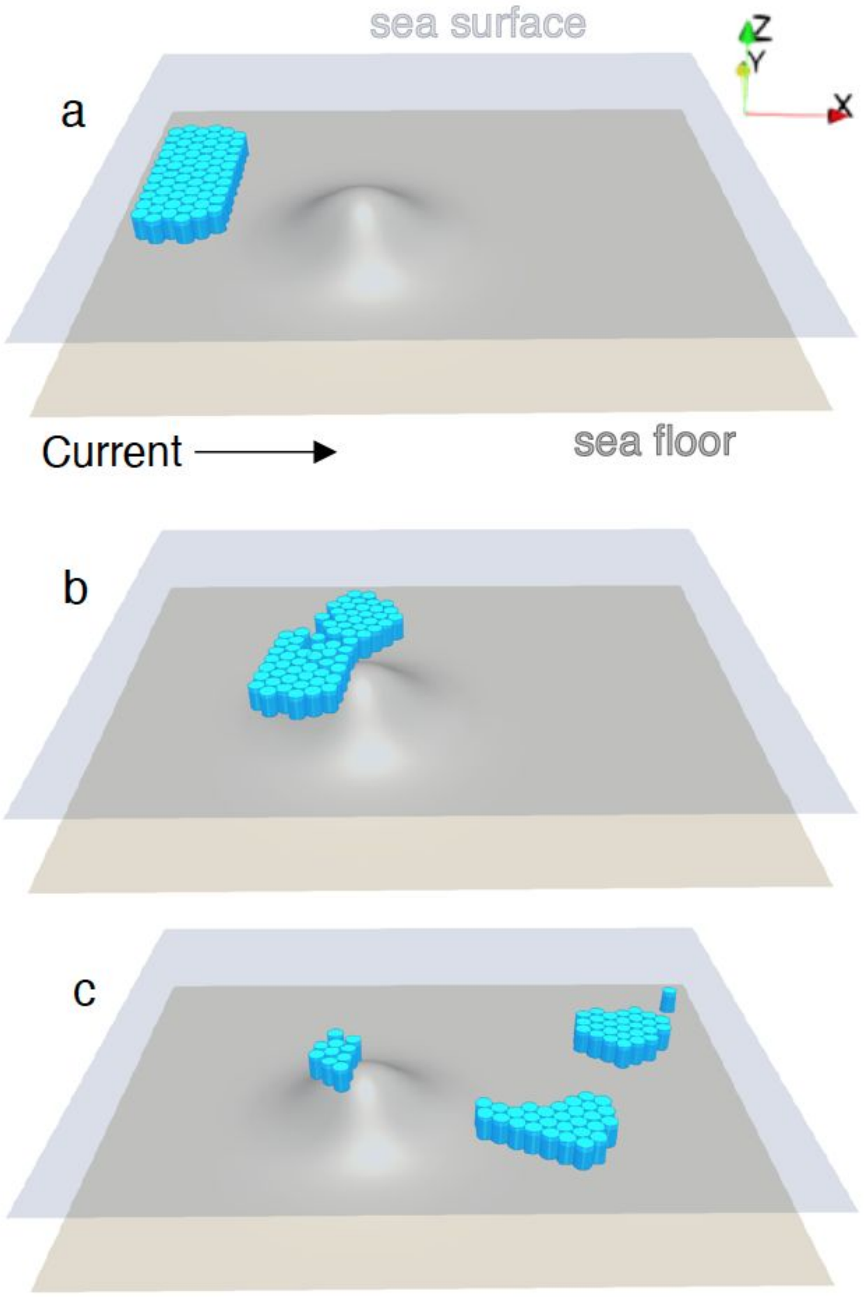
~1 trillion tons of meltwater in total

The Improved Kinematic Iceberg Dynamics (iKID) module

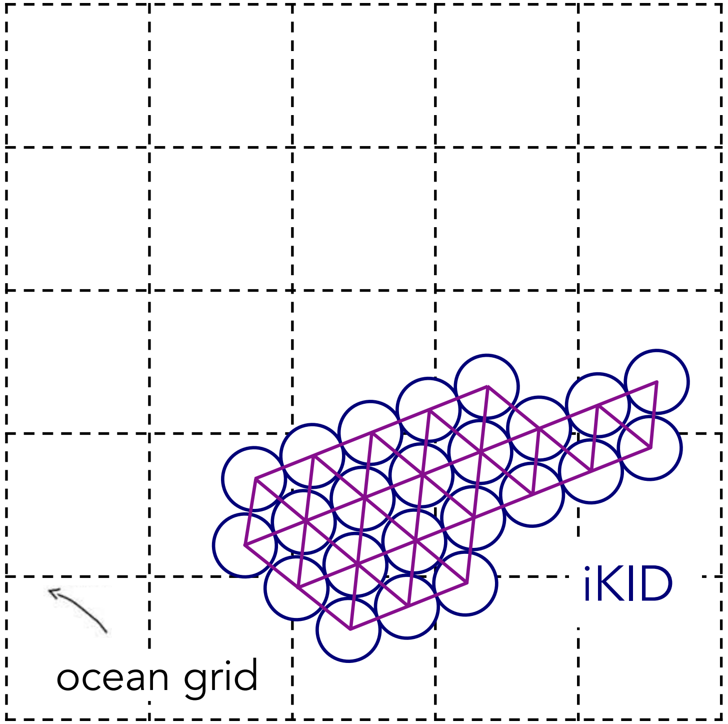


iKID captures:

- The true iceberg size and shape
- External forcings that vary across the iceberg body
- Internal stresses
- Grounding, rotation, contact between bergs, and "rift-calving"



iKID: A multiple time stepping (MTS) scheme increases computational efficiency



A68a simulation:

1 “long” step (“slow” forces) = 30 min

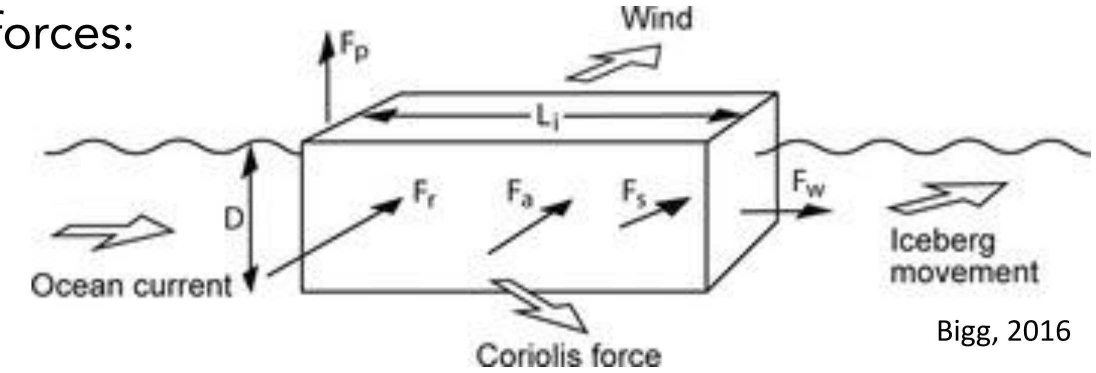
90 “short” sub-steps (“fast” forces) = 20 s

MTS scheme

1) Long step: external forces
2) *k* sub-steps:
   - Internal forces
   - Grounding
   - Position updates

iKID multiple time stepping scheme: long steps

Environmental forces:



Bigg, 2016

+ sea-ice drag
+ pressure gradient
(sea surface slope)

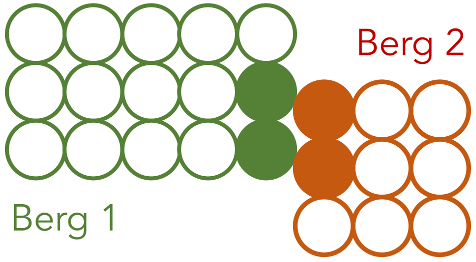
MTS scheme

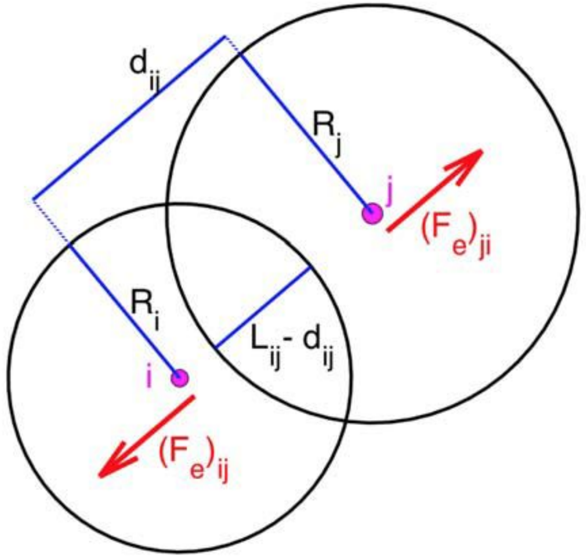
1) Long step: external forces

2) k sub-steps:
- Internal forces
- Grounding
- Position updates

Contact between bergs:

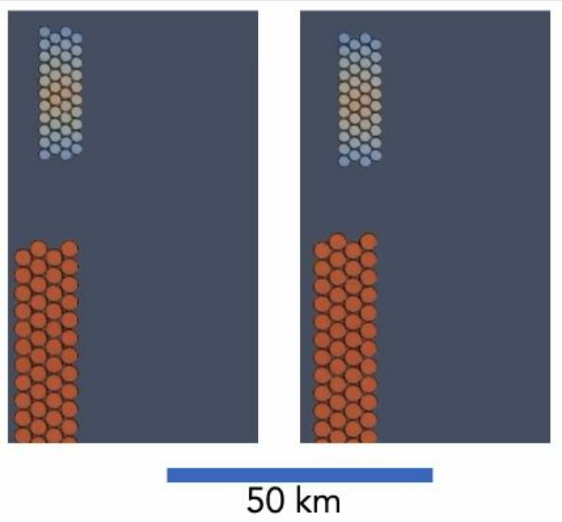
More efficient to evaluate on long step





$$(\vec{F}_{\mathrm{e}})_{ij} = -\kappa_{\mathrm{e}}(d_{ij} - L_{ij})m_{ij}\vec{r}_{ij}$$

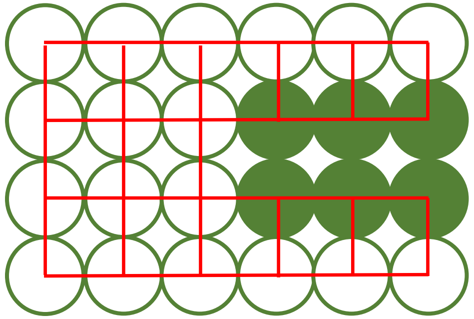
Use small contact spring constant for stability

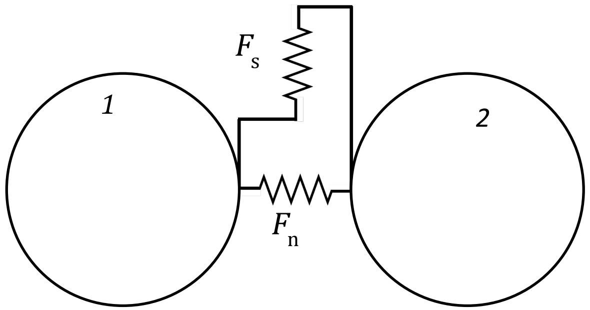


Increase "contact length" (L_{ij}) to prevent overlap

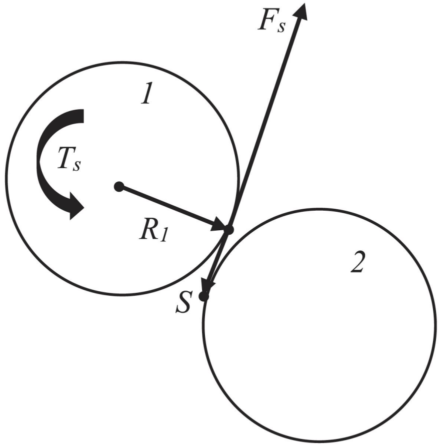
iKID multiple time stepping scheme: short steps

Interactive forces between particles in the same conglomerate

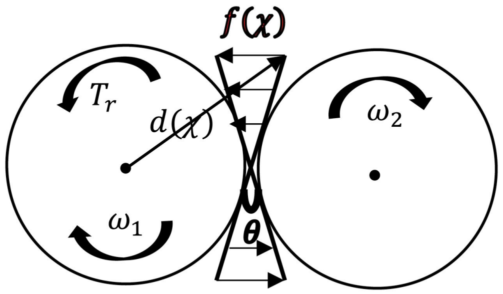




Normal and shear force



Torque from shear



Torque from relative rotation

MTS scheme

1) Long step: external forces

2) *k* short steps:
- Internal forces
- Grounding
- Position updates

Fracture criterion:

Break bonds when max tensile stress > tensile strength

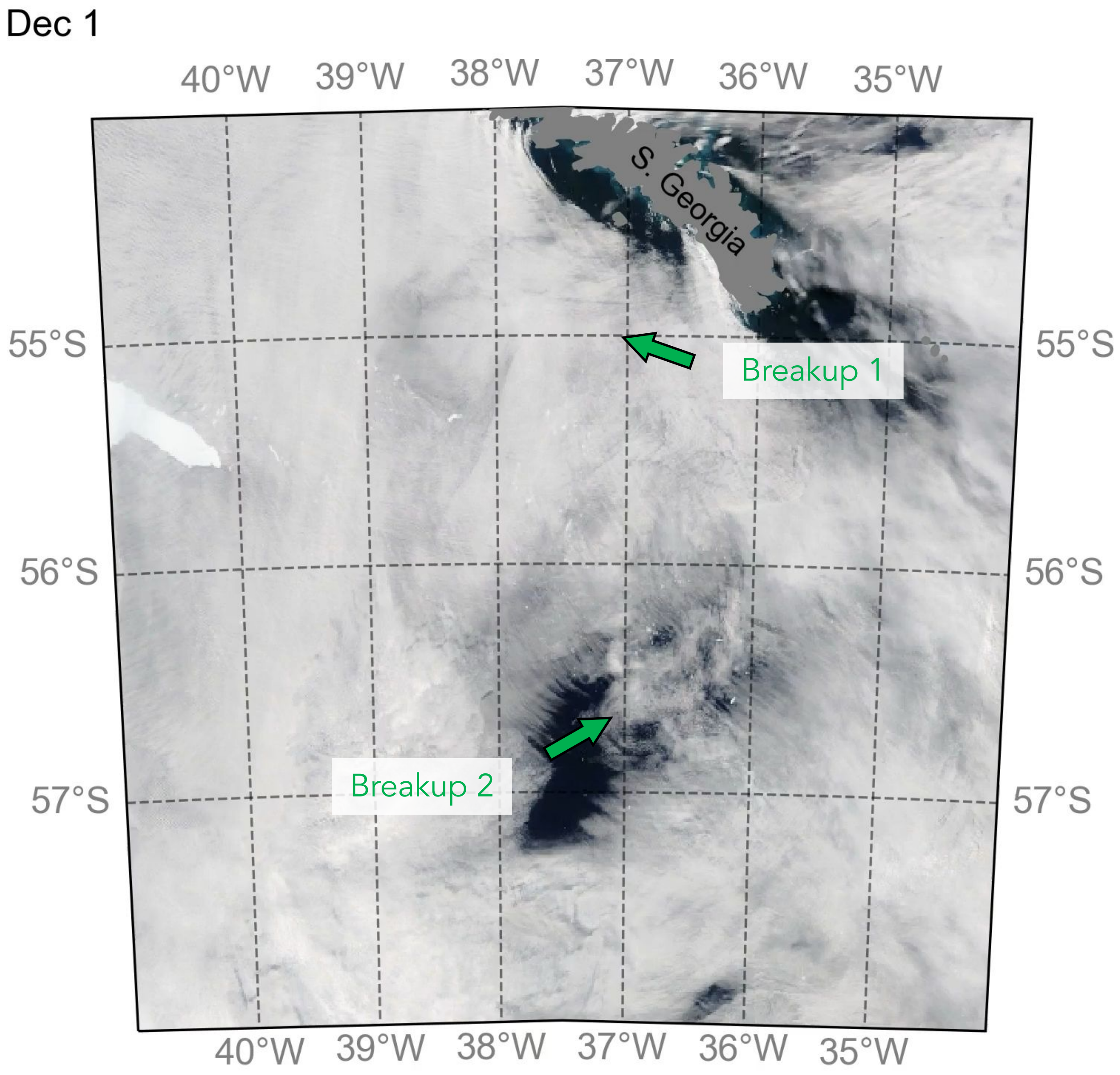
Grounding:

$$\vec{F}_{\mathrm{G}} = c_{\mathrm{g}} A \vec{u}$$

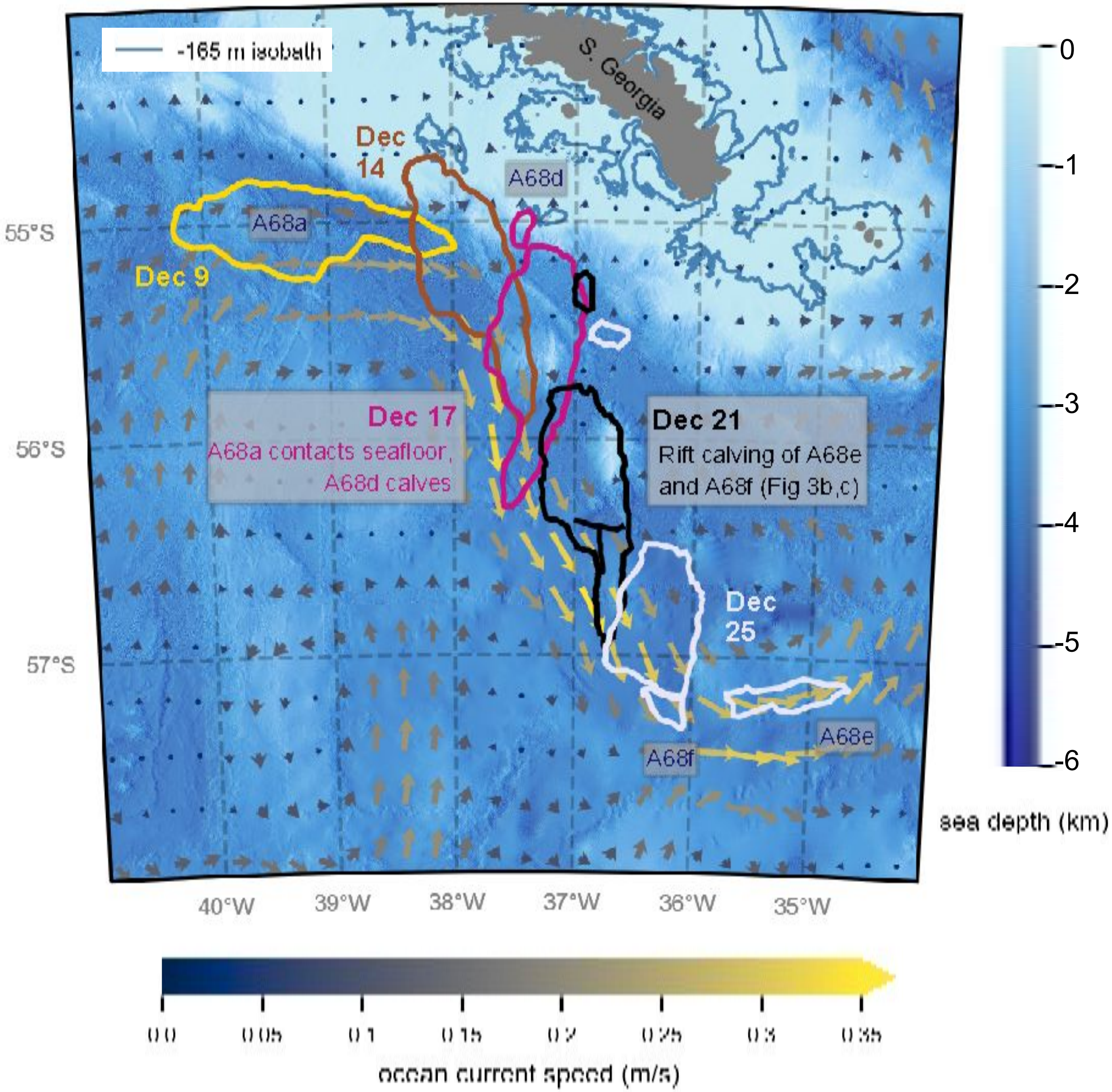
Test case:

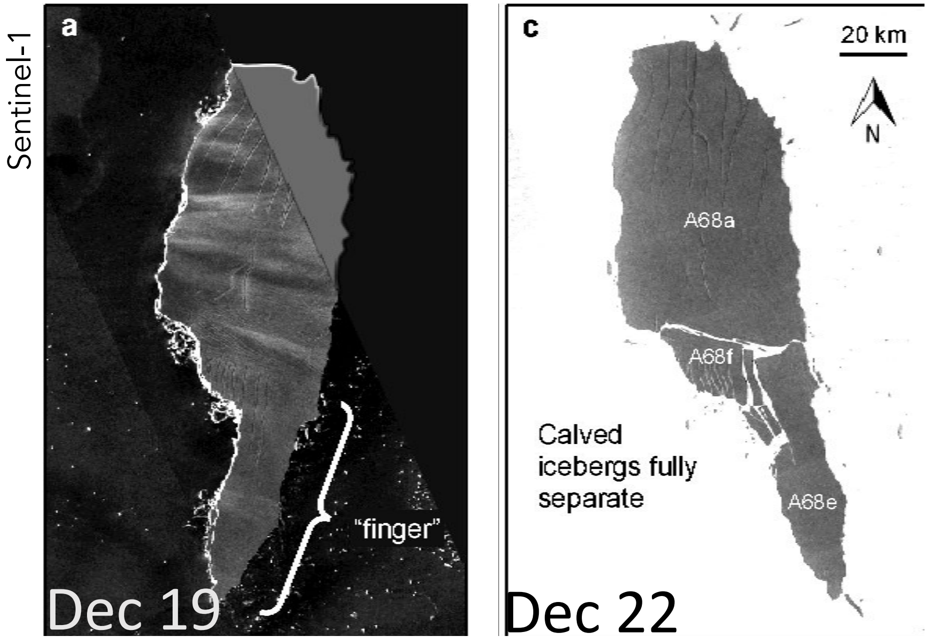
Can we simulate the December 2020 drift and breakup of Iceberg A68a?

What caused the second breakup event?



NASA MODIS Aqua/Terra





Finger was fully intact between breakups

2nd breakup occurs when finger overlaps stronger currents

Hypothesis: Second rift calving was caused by ocean-current shear

- This breakup mechanism has not been reported previously
- Can be tested with iKID

iKID A68a simulation

Data sources

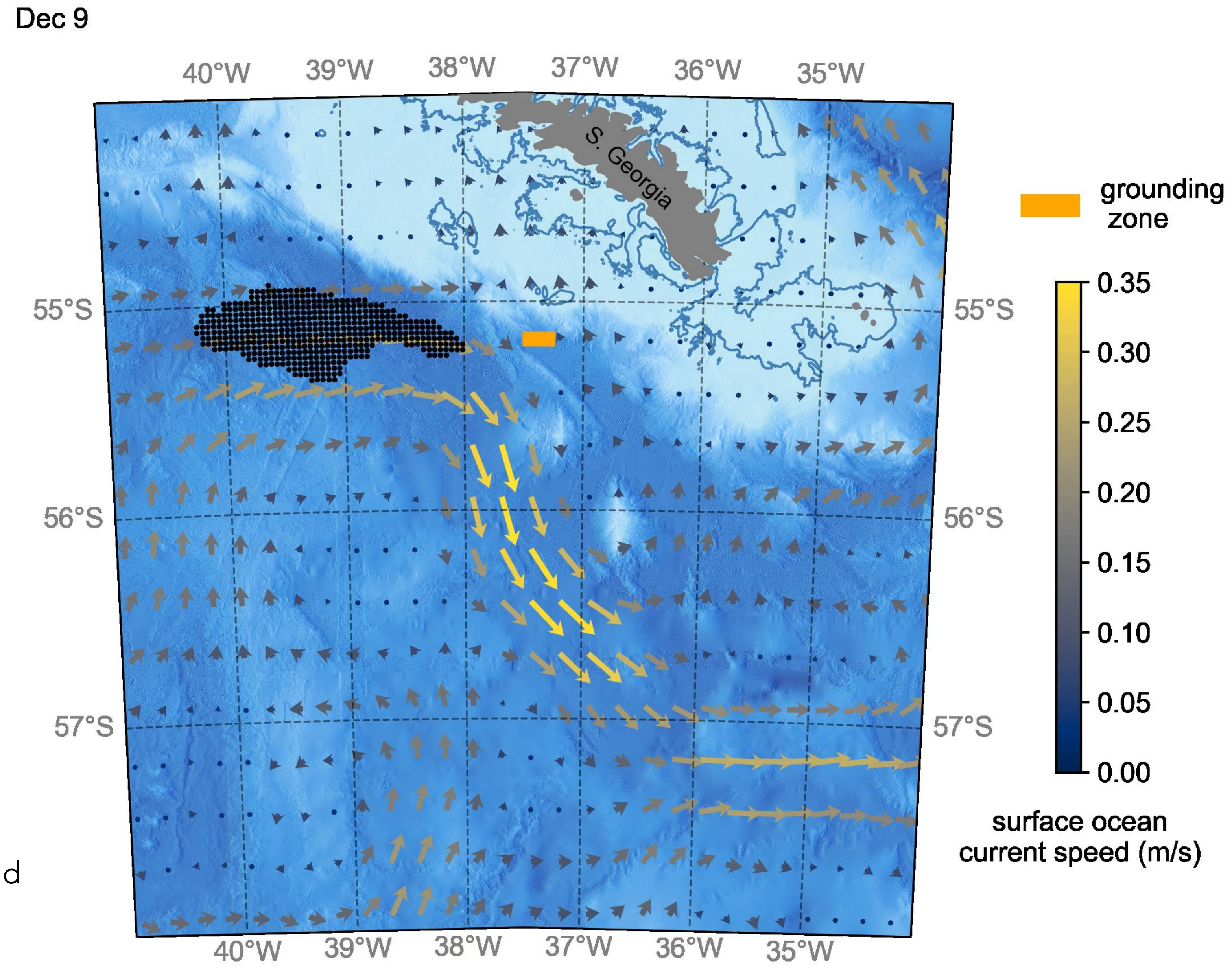
- ESR/OSCAR surface ocean current velocities
- SSALTO/DUACS sea surface heights
- NCEP/NCAR 10 m reanalysis vector winds

Tuning

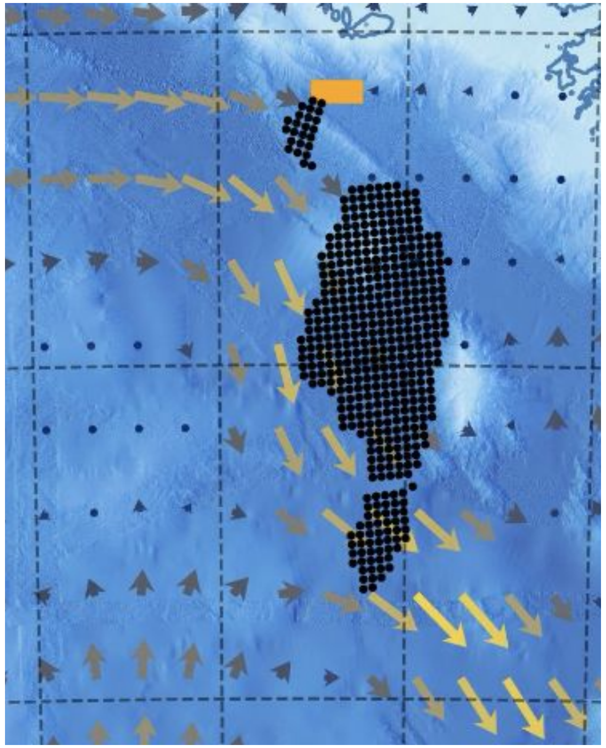
- Each particle is 200 m thick with a 1.5 km radius
- Tensile bond strength: 18 kPa
  - MacAyeal et al, 2008 estimated of order 10 kPa

MTS scheme clock-time

- ∽ 8 s to simulate each day of iceberg evolution
- Sufficient for climate modeling
- Further speedup with coarser particle resolution and optimization



Study 2 Summary



- Ocean-current shear may trigger some iceberg breakups
  - Longer bergs may be more susceptible
- The iKID bonded-particle iceberg model
  - Represents true iceberg size, shape, and stress
  - Captures rotation, rift-calving, grounding, etc.
- However, iKID is currently only ready for specialized applications
  - Point-particles + footloose is ready for generalized use within climate models

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Huth et al., 2022. **Ocean currents break up a tabular iceberg**. *Science Advances.*

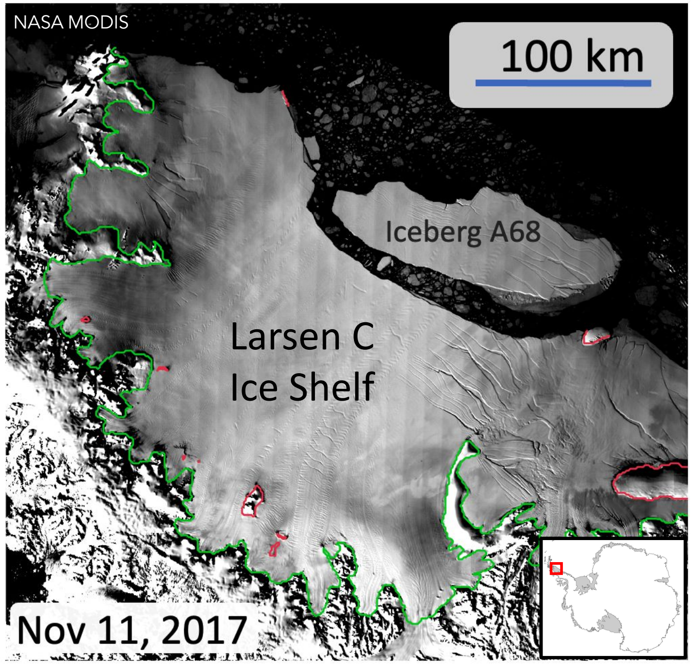
Next steps

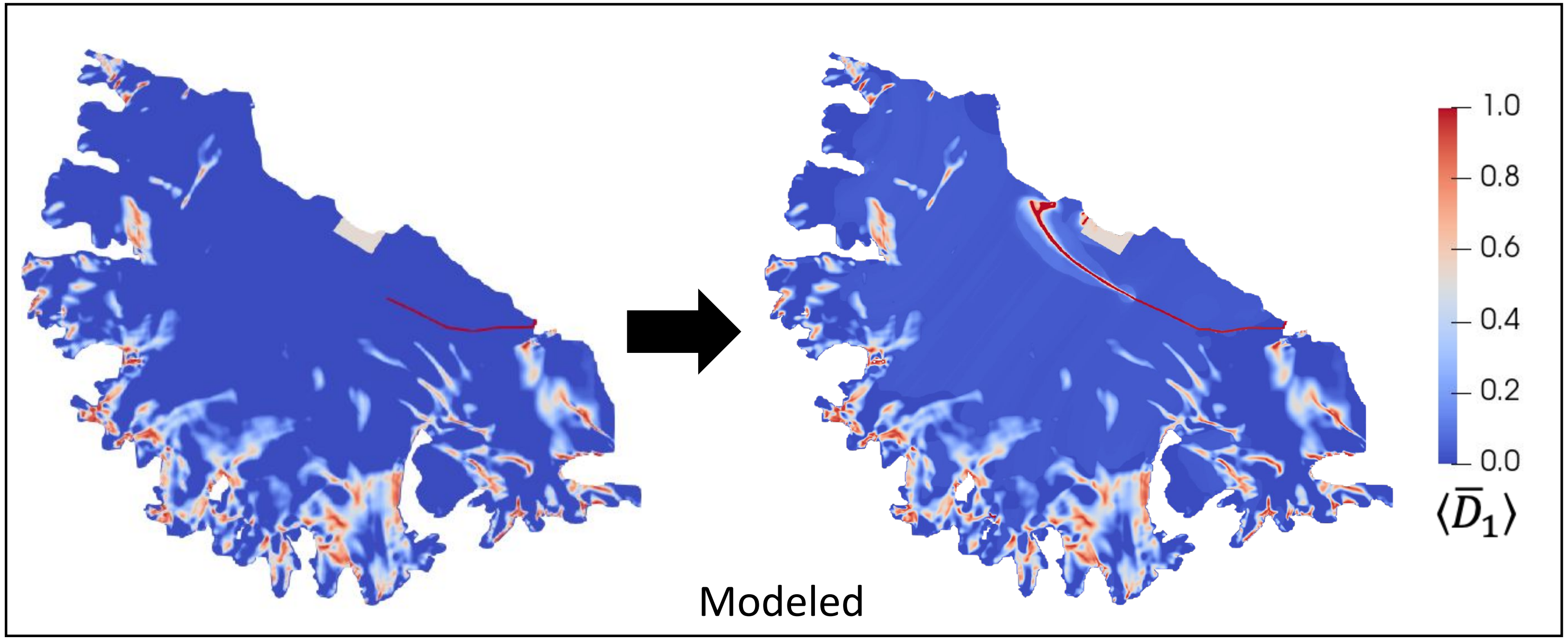
Develop capabilities to:

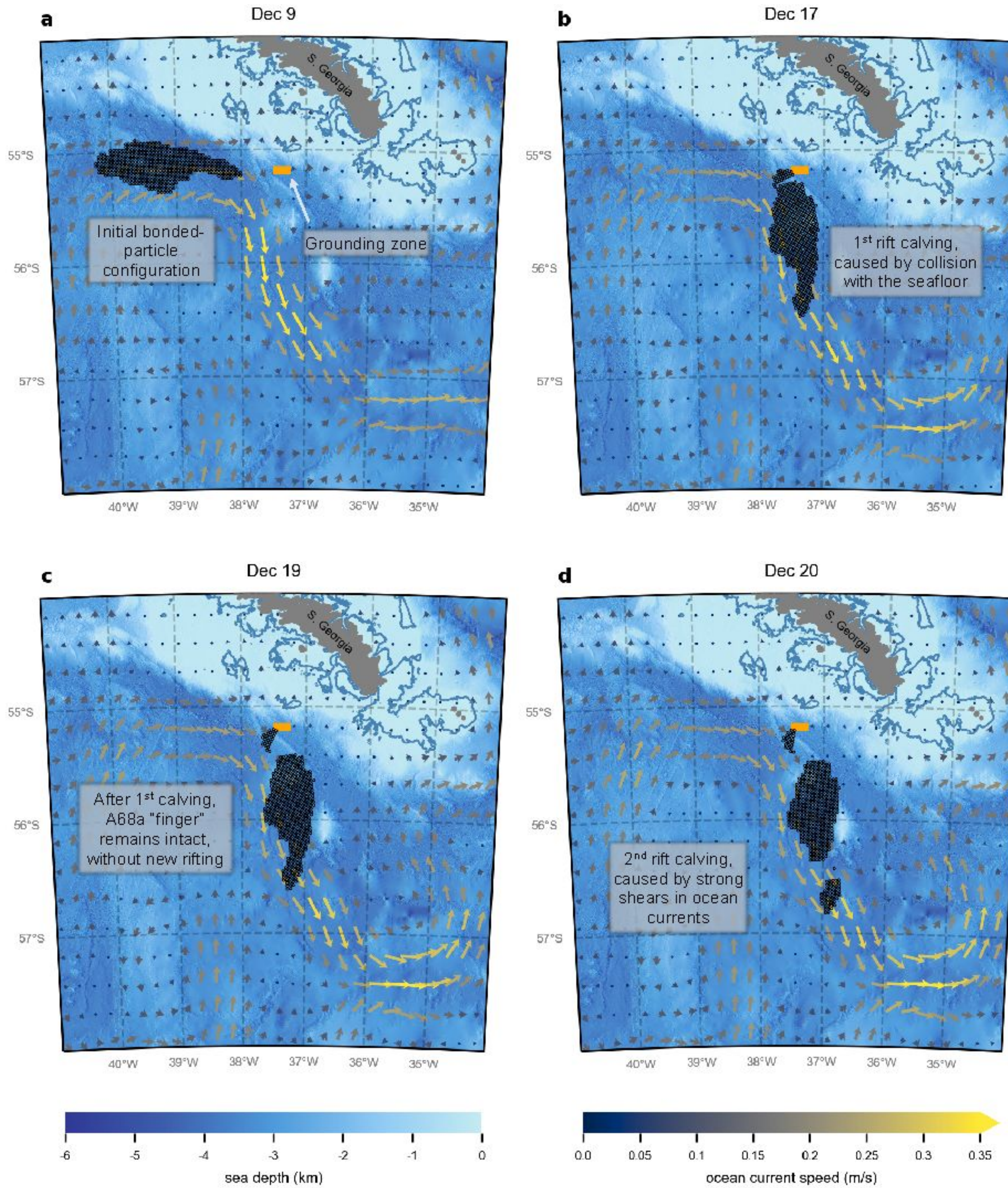
- Calve iKID icebergs from ice shelves within Earth system models
- Displace ocean and sea-ice
- Atmospheric coupling + hydrofracture

Related work:

Huth et al. (2023) "Modeling the Processes that Control Ice-Shelf Rift Paths Using Damage Mechanics". *In revision.*






a
Dec 9
S. Georgia
55°S
56°S
57°S
Initial bonded-particle configuration
Grounding zone
40°W
39°W
38°W
37°W
36°W
35°W
b
Dec 17
1st rift calving, caused by collision with the seafloor
c
Dec 19
After 1st calving, A68a "finger" remains intact, without new rifting
d
Dec 20
2nd rift calving, caused by strong shears in ocean currents
-6
-5
-4
-3
-2
-1
0
sea depth (km)
0.0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
ocean current speed (m/s)