Iceberg dynamics in glacial and modern oceans

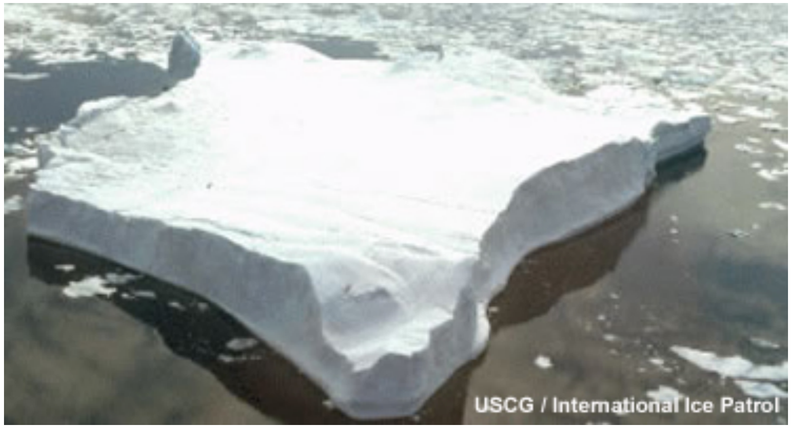
Ian Eisenman

Collaborators: **Till Wagner**, Rebecca Dell, Ralph Keeling, Jeff Severinghaus, Laurie Padman

Intro: Iceberg basics

• Icebergs are blocks of freshwater ice that **calve** off a glacier or ice shelf (mainly in **Greenland** and **Antarctica**).

• Typical size: 100s by 10s of m in Greenland, larger (~15km) in Antarctica.



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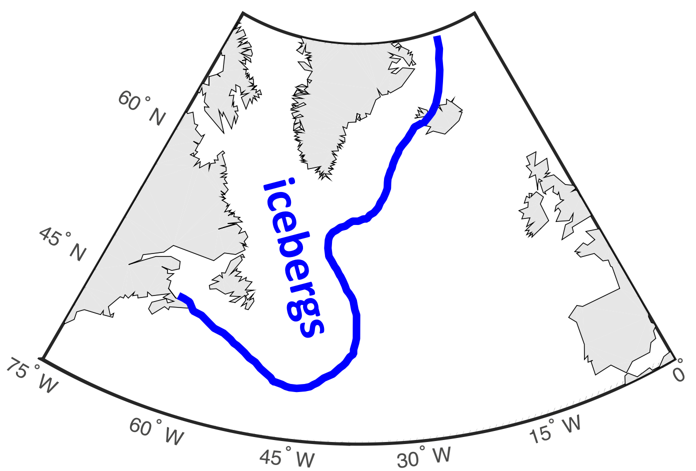
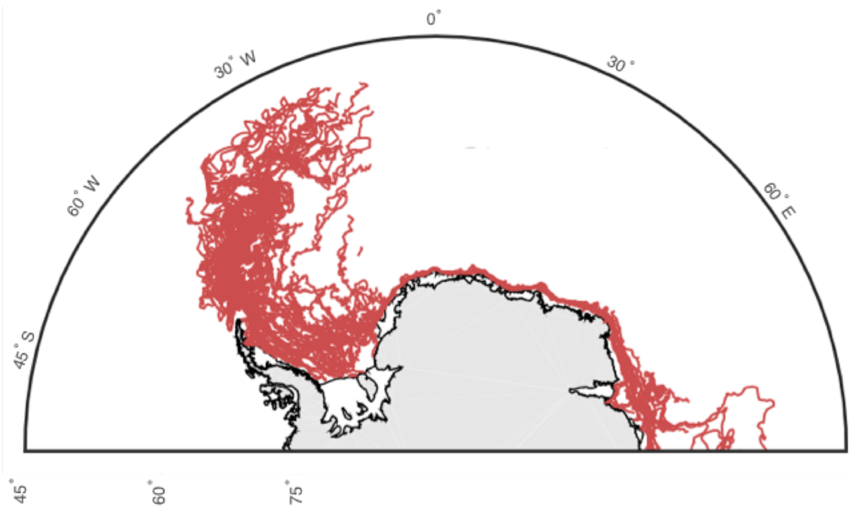
• Typical size: 100s by 10s of m in Greenland, larger (~15km) in Antarctica.

• Mass loss primarily from **wave erosion of the sidewall** (~1 m/day).

• Drift 1,000s of km during lifetime of ~1 yr: found in western North Atlantic and Southern Ocean.



Normal range of icebergs from International Ice Patrol (2010)

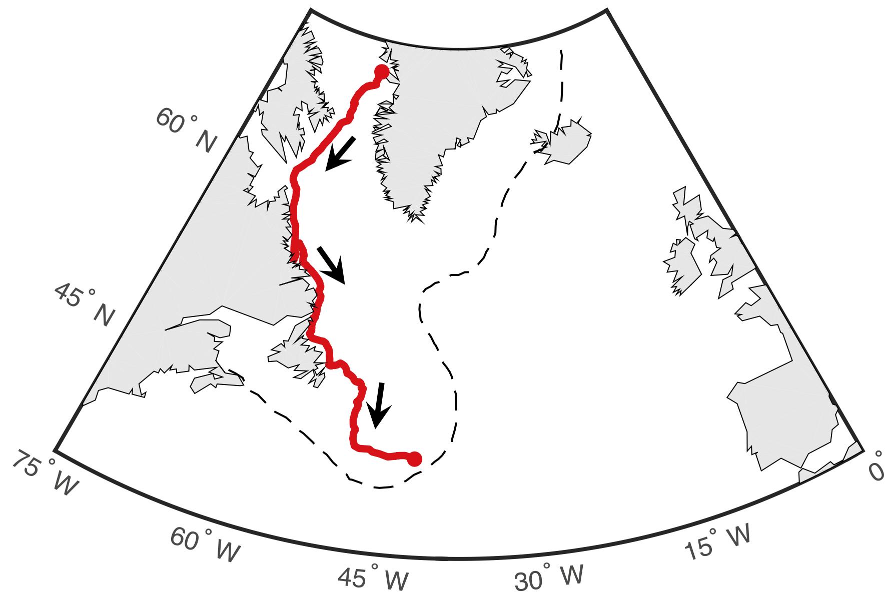


Satellite-derived trajectories from Ballantyne and Long (2002)

Intro: Iceberg meltwater

• Iceberg freshwater flux **influences ocean circulation** through effect on seawater density.

• Empirical **rule-of-thumb**: icebergs drift at **2% of wind velocity** relative to ocean current.



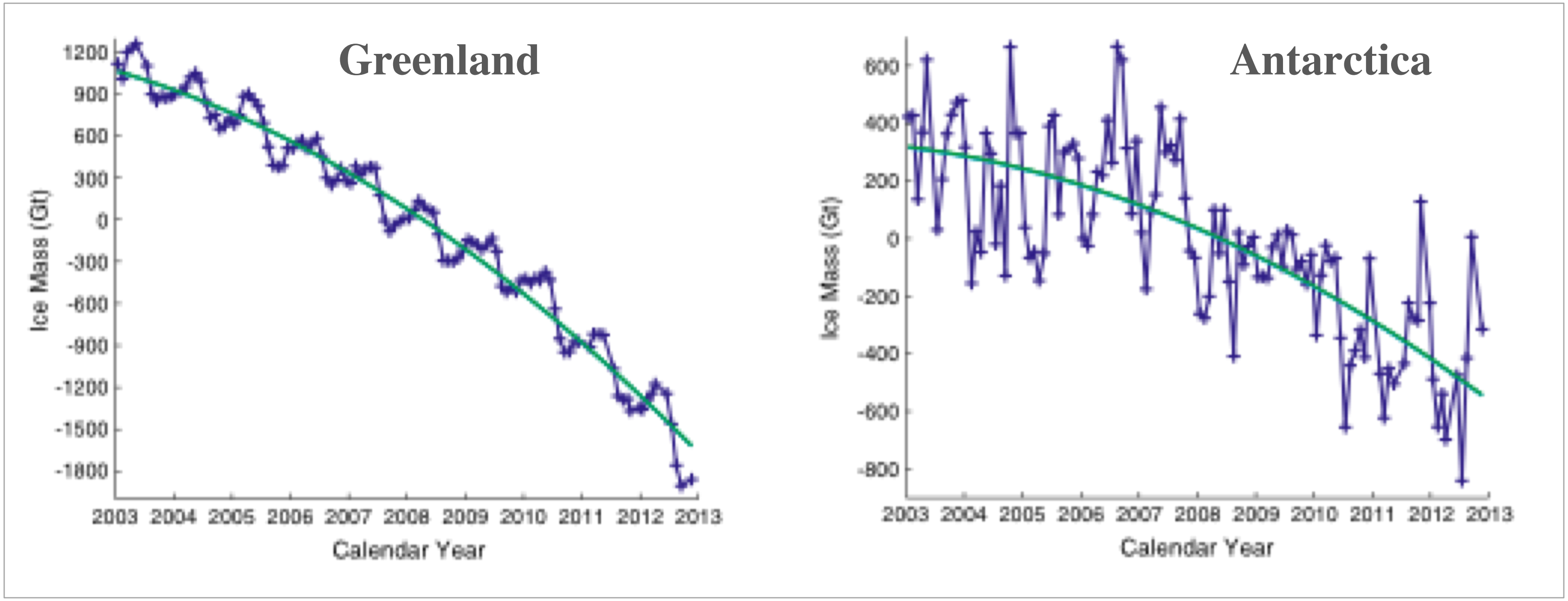
• This has been **observed in many empirical studies** (Garrett et al. 1985, Smith and Donaldson 1987, Smith 1993, etc) and reproduced in numerical models (e.g., Bigg et al. 1997), but it has **never previously been physically derived or justified**.

• **Why 2%? Where does this approximation break down?**

• **Goal #1: Analytically derive 2% rule.**

Intro: Observed changes

- **Increasing discharge during recent years** (e.g., Rignot et al. 2011, Velicogna & Wahr 2013).



Velicogna and Wahr, 2013

Intro: Projected changes

• Projections suggest **massive increases during the coming century** (e.g., Nick et al. 2013, Joughin et al. 2014, DeConto & Pollard 2016).

• **Huge iceberg discharges**, called **Heinrich Events**, are believed to have occurred during the **last glacial period**, disrupting the global climate (e.g., Broecker 1994, Hemming 2004, Stokes et al. 2015).

"All the News That's Fit to Print"

The New York Times

Late Edition

Today, partly sunny, cooler, less humid, high 69. **Tonight,** partly cloudy, seasonable, low 52. **Tomorrow,** periods of clouds and sunshine, high 67. Weather map is on Page C8.

VOL. CLXVI . . . No. 57,603 © 2017 The New York Times Company NEW YORK, SATURDAY, MAY 20, 2017 $2.50

JONATHAN CORUM/THE NEW YORK TIMES

Antarctic Dispatches: A Continent at Risk

The Ross Ice Shelf, a floating chunk of ice the size of California, is stable for now. But a rapid disintegration of Antarctic ice could raise the sea level by as much as six feet by the middle of the century, deluging major coastal cities, including New York. Page A11.

Leaving Stress As More Waits In Trip Abroad

Tumult at Home Raises Stakes for President

By PETER BAKER

WASHINGTON — President Trump embarked on Friday on his first foreign mission since taking office, beginning a challenging nine-day, multistop, multifaceted journey to the Middle East and Europe and leaving behind a capital consumed by investigations and intrigue.

Mr. Trump's first stop will be Riyadh, Saudi Arabia, where he will meet with dozens of Arab and Muslim leaders. He will later travel to Jerusalem, Bethlehem, Vatican City, Brussels and finally Sicily before returning May 27.

An inaugural foreign trip would have been daunting for a diplomatic novice under any circumstances, given the panoply of complicated issues that will confront Mr. Trump, including terrorism, religion, economics, Middle East peace, the war in Afghanistan, the future of NATO and Russian aggression. But it will be only more so given the distractions back home as a newly appointed special counsel begins

TRUMP ADMITTED DISMISSAL AT F.B.I. EASED PRESSURE

CALLED COMEY 'NUT JOB'

Remarks to Russians in the Oval Office a Day After the Firing

*This article is by **Matt Apuzzo**, **Maggie Haberman** and **Matthew Rosenberg**.*

WASHINGTON — President Trump told Russian officials in the Oval Office this month that firing the F.B.I. director, James B. Comey, had relieved "great pressure" on him, according to a document summarizing the meeting.

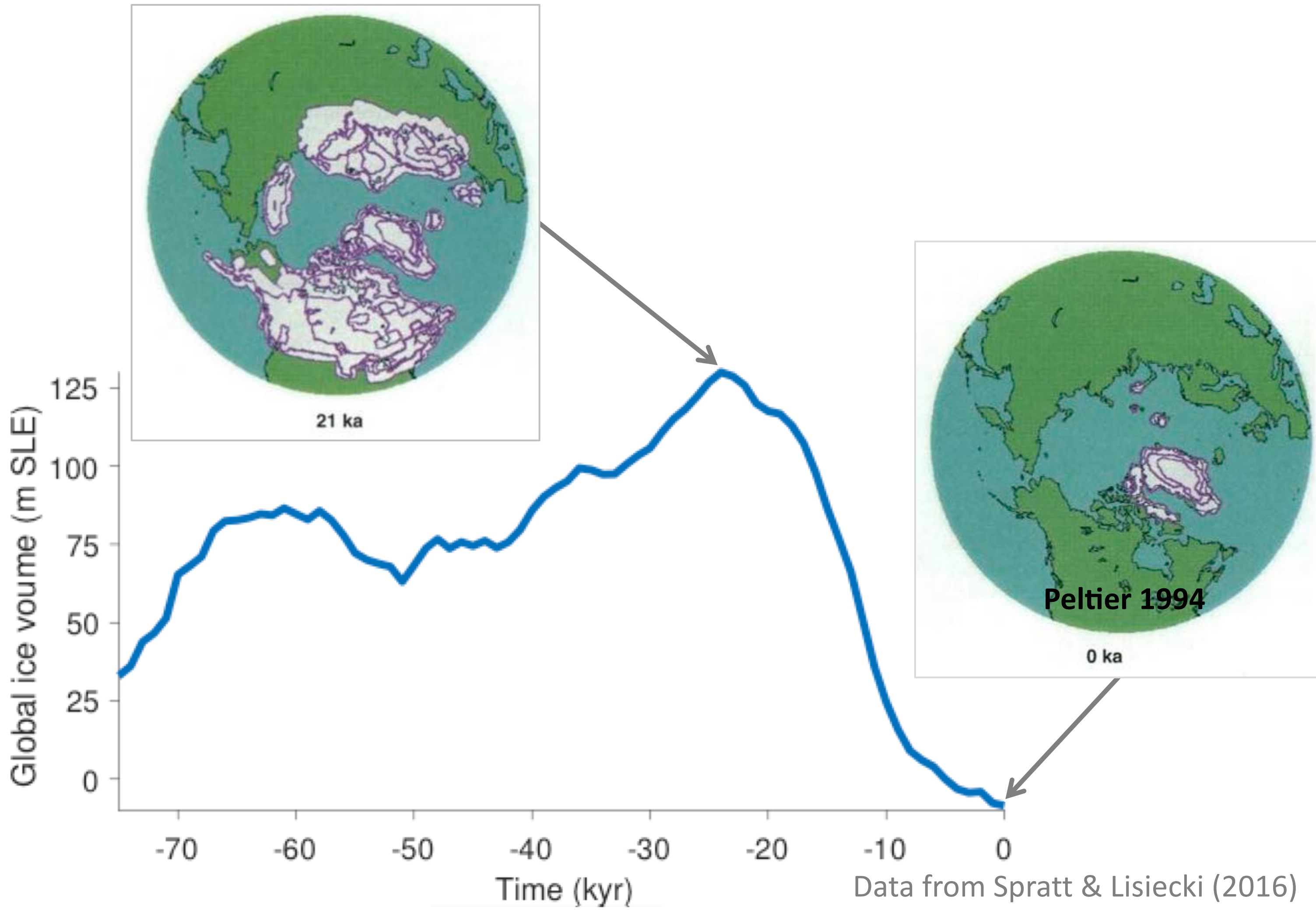
"I just fired the head of the F.B.I. He was crazy, a real nut job," Mr. Trump said, according to the document, which was read to The New York Times by an American official. "I faced great pressure because of Russia. That's taken off."

Mr. Trump added, "I'm not under investigation."

The conversation, during a May 10 meeting — the day after he fired Mr. Comey — reinforces the notion that the president dismissed

Intro: Heinrich Events

• During the **last glacial period** (about 100 ka until 20 ka), the Laurentide Ice Sheet covered much of North America.

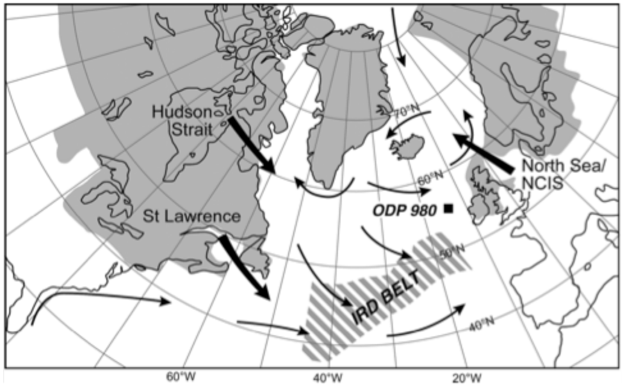


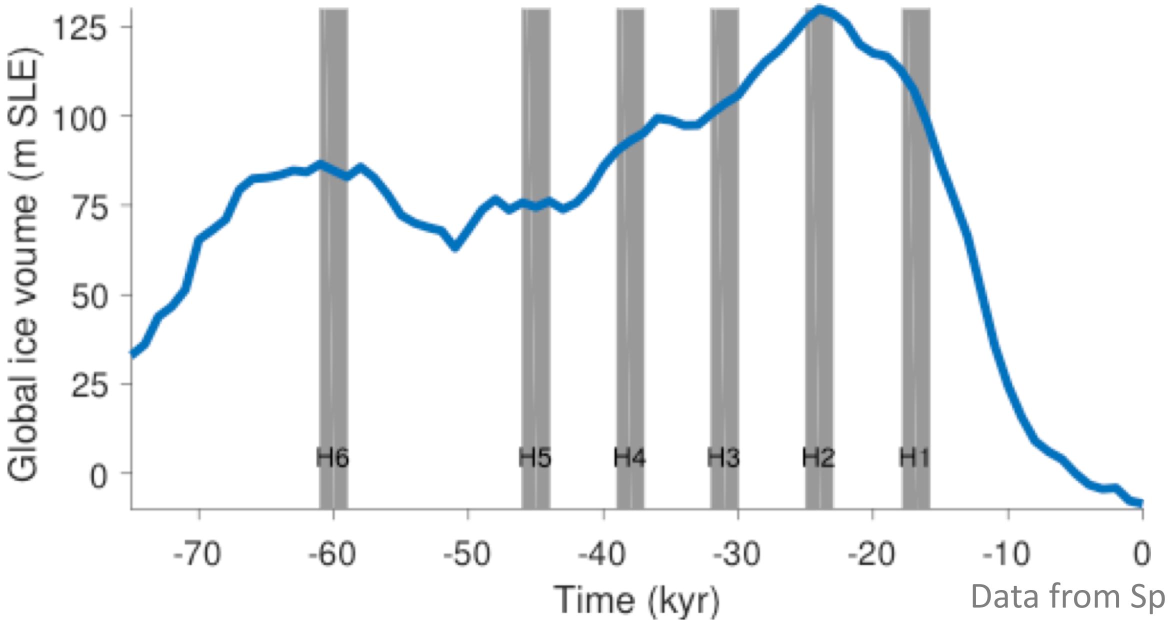
Data from Spratt & Lisiecki (2016)

Intro: Heinrich Events

- During the **last glacial period** (about 100 ka until 20 ka), the Laurentide Ice Sheet covered much of North America.

- Sediment cores in the North Atlantic (40°N-55°N) contain layers of "**ice rafted debris**" (IRD), indicating vast armadas of icebergs (Heinrich 1988).





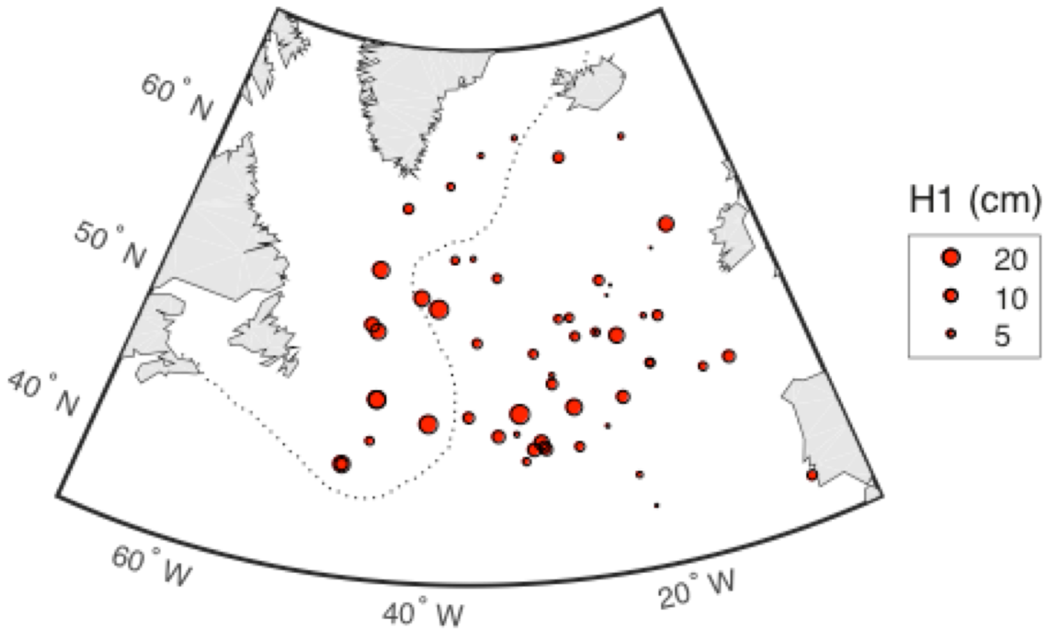
Data from Spratt & Lisiecki (2016)

Intro: Map of Heinrich IRD layers

- IRD layers in sediment cores provide a **record of iceberg drift and decay**.

- Layer thickness is far **more zonally uniform** than would be expected, implying **trajectories strikingly different than today**.

- **Goal #2: Address enigma of how icebergs traveled so far.**



Roadmap

- Construct Lagrangian **model of iceberg drift and decay**, building on previous studies.
    - Physically **derive the empirical rule of thumb** that $\vec{v}_i = \vec{v}_w + 2\% \, \vec{v}_a$.
    - **Validate** the model using an ocean state estimate and iceberg observations.
- **Simulate Heinrich Event IRD** deposition in glacial climate.
- **Propose and test a mechanism** for enhanced iceberg spread during Heinrich Events.

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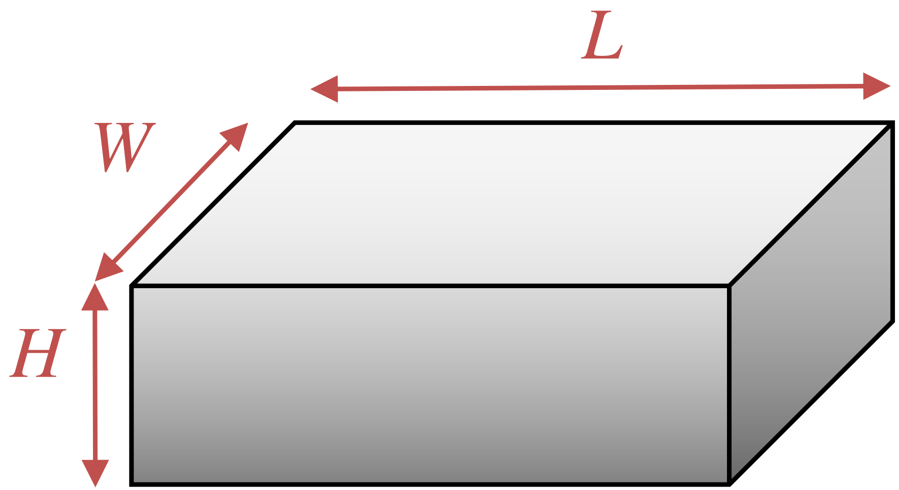
Iceberg model: Ingredients

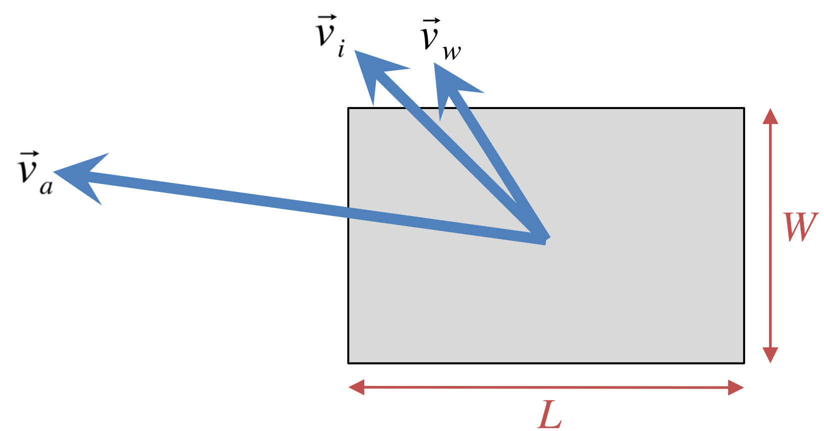


- **Drift**: Iceberg velocity as function of ocean currents and winds.
- **Decay**: Primarily wave erosion; also side melt and basal melt.

Governing equations

$$\underbrace{\boxed{M\frac{d\vec{v}_i}{dt}}}_{\text{inertia}} = \underbrace{\boxed{-Mf\hat{k}\times\vec{v}_i}}_{\text{Coriolis}} + \underbrace{\boxed{\vec{F}_w}}_{\text{water drag}} + \overbrace{\boxed{\vec{F}_a}}^{\text{air drag}} + \underbrace{\boxed{\vec{F}_p}}_{\text{pressure gradient force}} + \overbrace{\boxed{\vec{F}_r}}^{\text{wave radiation}} + \underbrace{\boxed{\vec{F}_i}}_{\text{sea ice}}$$

(e.g., Bigg et al. 1997)



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Approximations

$$\boxed{M\frac{d\vec{v}_i}{dt}} = \boxed{-Mf\hat{k}\times\vec{v}_i} + \boxed{\vec{F}_w} + \boxed{\vec{F}_a} + \boxed{\vec{F}_p} + \boxed{\vec{F}_r} + \boxed{\vec{F}_i}$$

inertia, Coriolis, water drag, air drag, pressure gradient force, wave radiation, sea ice

1. iceberg acceleration is small
2. drag from sea ice and wave radiation are small (e.g., Bigg et al. 1997, Gladstone et al. 2001)
3. pressure gradient force approximated from geostrophic ocean velocity (e.g., Smith & Banke 1983, Gladstone et al. 2001, Stern at al. 2016)
4. iceberg velocity is much smaller than air velocity

Approximations

$$\underbrace{\cancel{M\frac{d\vec{v}_i}{dt}}}_{\text{inertia}\ \to\ 0} = \underbrace{-Mf\hat{k}\times\vec{v}_i}_{\text{Coriolis}} + \underbrace{\vec{F}_w}_{\text{water drag}} + \overbrace{\vec{F}_a}^{\text{air drag}} + \underbrace{\vec{F}_p}_{\text{pressure gradient force}} + \overbrace{\vec{F}_r}^{\text{wave radiation}} + \underbrace{\vec{F}_i}_{\text{sea ice}}$$

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   (e.g., Smith & Banke 1983, Gladstone et al. 2001, Stern at al. 2016)
   $\rightarrow \vec{F}_p \equiv -\frac{M}{\rho_w}\nabla P \approx Mf\hat{k}\times\vec{v}_w$
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Approximations

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Insert standard representations of water and air form drag:

$$\vec{F}_w = \tfrac{1}{2}\rho_w C_w A_w \left|\vec{v}_w - \vec{v}_i\right| \left(\vec{v}_w - \vec{v}_i\right), \quad A_w = \frac{\rho_i}{\rho_w}\,\frac{2}{\pi}(L+W)H$$

$$\vec{F}_a = \tfrac{1}{2}\rho_a C_a A_a \left|\vec{v}_a - \vec{v}_i\right| \left(\vec{v}_a - \vec{v}_i\right), \quad A_a = \frac{\rho_w - \rho_i}{\rho_i} A_w$$

Approximations

Coriolis & PGF — water drag — air drag

$$0 = Mf\hat{k} \times \left(\vec{v}_w - \vec{v}_i\right) + \tfrac{1}{2}\rho_w C_w A_w \left|\vec{v}_w - \vec{v}_i\right| \left(\vec{v}_w - \vec{v}_i\right) + \tfrac{1}{2}\rho_a C_a A_a \left|\vec{v}_a - \vec{v}_i\right| \left(\vec{v}_a - \vec{v}_i\right)$$

Approximations

Coriolis & PGF   water drag   air drag

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4. **iceberg velocity is much smaller than air velocity**

Analytical solution

$$\overset{\text{Coriolis \& PGF}}{0 = M f \hat{k} \times \left(\vec{v}_w - \vec{v}_i\right)} + \overset{\text{water drag}}{\tfrac{1}{2}\rho_w C_w A_w \left|\vec{v}_w - \vec{v}_i\right| \left(\vec{v}_w - \vec{v}_i\right)} + \overset{\text{air drag}}{\tfrac{1}{2}\rho_a C_a A_a \left|\vec{v}_a\right| \left(\vec{v}_a\right)}$$

$$\boxed{\vec{v}_i = \vec{v}_w + \gamma\left(-\alpha \hat{k} \times \vec{v}_a + \beta \vec{v}_a\right)}$$

$$\gamma \equiv \left(\frac{\rho_w C_w A_w}{\rho_a C_a A_a}\right)^{1/2} = \left[\frac{\rho_a\left(\rho_w - \rho_i\right)}{\rho_w \rho_i}\frac{C_a}{C_w}\right]^{1/2}$$

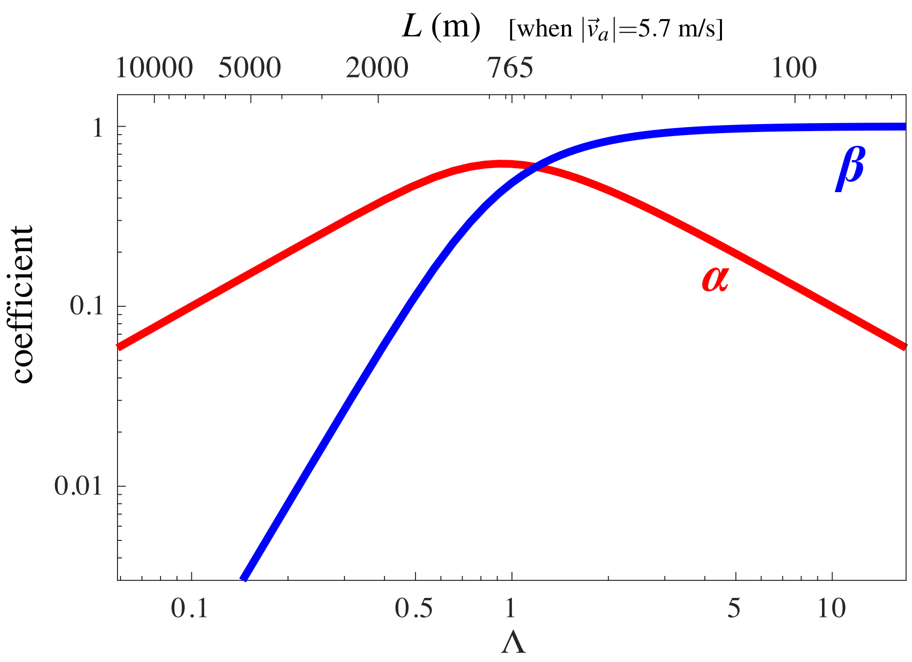
$$\alpha \equiv \frac{1}{2\Lambda^3}\left(\sqrt{1+4\Lambda^4} - 1\right) \qquad \beta \equiv \frac{1}{\sqrt{2}\Lambda^3}\left[\left(1+\Lambda^4\right)\sqrt{1+4\Lambda^4} - 3\Lambda^3 - 1\right]^{1/2}$$

$$\Lambda \equiv \frac{\gamma C_w}{\pi f}\frac{\left|\vec{v}_a\right|}{S} \qquad S \equiv \frac{LW}{L+W}$$

Asymptotic limits

across-wind downwind

$$\vec{v}_i = \vec{v}_w + \gamma\left(-\alpha\hat{k}\times\vec{v}_a + \beta\vec{v}_a\right)$$



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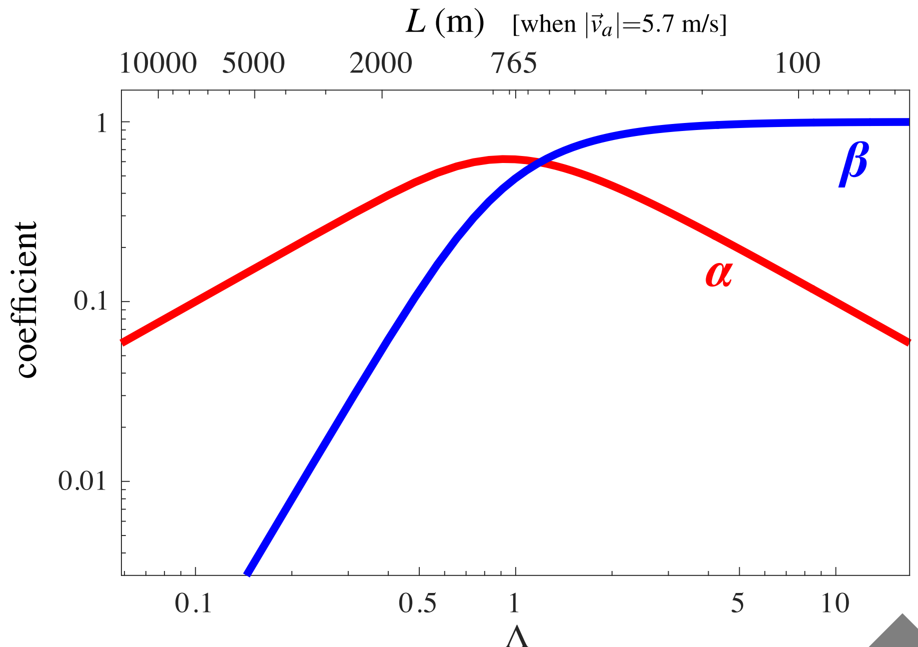

small icebergs

$$\vec{v}_i = \vec{v}_w + \gamma\beta\vec{v}_a$$

$$\beta = 1, \qquad \gamma = \left[\frac{\rho_a\left(\rho_w - \rho_i\right)}{\rho_w\rho_i}\frac{C_a}{C_w}\right]^{1/2} = \mathbf{0.02}$$

In **agreement with longstanding empirical rule-of-thumb** (e.g., Garrett et al. 1985, Smith and Donaldson 1987, Smith 1993, Bigg et al. 1997)

Asymptotic limits

across-wind downwind

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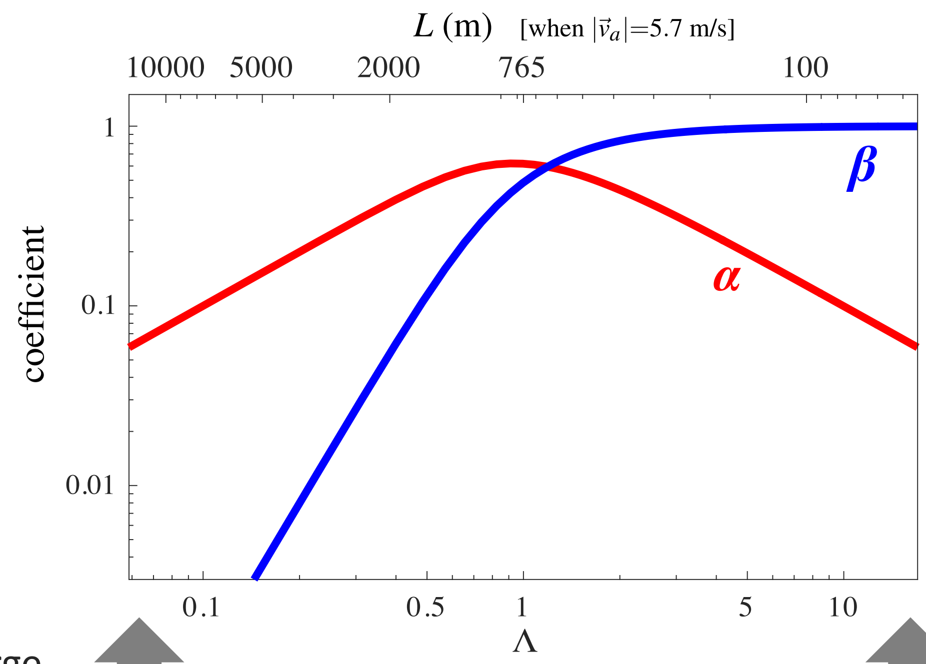


large icebergs

small icebergs

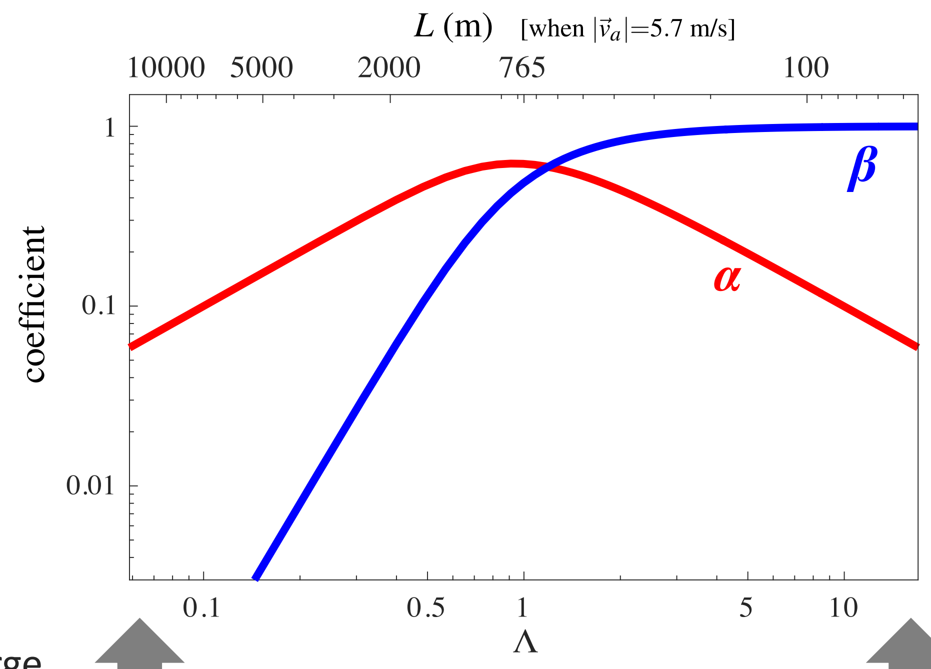
$$\vec{v}_i = \vec{v}_w$$

$$\vec{v}_i = \vec{v}_w + 2\%\ \vec{v}_a$$

Asymptotic limits

across-wind downwind

$$\vec{v}_i = \vec{v}_w + \gamma\left(-\alpha\hat{k}\times\vec{v}_a + \beta\vec{v}_a\right)$$



large icebergs

small icebergs

$$\vec{v}_i = \vec{v}_w$$

$$\vec{v}_i = \vec{v}_w + 2\%\ \vec{v}_a$$

Antarctic

Arctic

Explanation of 2% rule

$$0 = \overbrace{\underbrace{M}_{L^2\,H} f\hat{k}\times\left(\vec{v}_w - \vec{v}_i\right)}^{\text{Coriolis \& PGF}} + \overbrace{\tfrac{1}{2}\rho_w C_w \underbrace{A_w}_{L\,H} \left|\vec{v}_w - \vec{v}_i\right|\left(\vec{v}_w - \vec{v}_i\right)}^{\text{water drag}} + \overbrace{\tfrac{1}{2}\rho_a C_a \underbrace{A_a}_{L\,H} \left|\vec{v}_a\right|\left(\vec{v}_a\right)}^{\text{air drag}}$$

Small L: $\tfrac{1}{2}\rho_w C_w A_w \left|\vec{v}_i - \vec{v}_w\right|\left(\vec{v}_i - \vec{v}_w\right) = \tfrac{1}{2}\rho_a C_a A_a \left|\vec{v}_a\right|\left(\vec{v}_a\right)$

$$\vec{v}_i = \vec{v}_w + \left(\frac{\rho_a C_a A_a}{\rho_w C_w A_w}\right)^{1/2}\vec{v}_a = \vec{v}_w + 2\%\,\vec{v}_a$$

Large L: $Mf\hat{k}\times\left(\vec{v}_w - \vec{v}_i\right) = 0$

$$\vec{v}_i = \vec{v}_w$$

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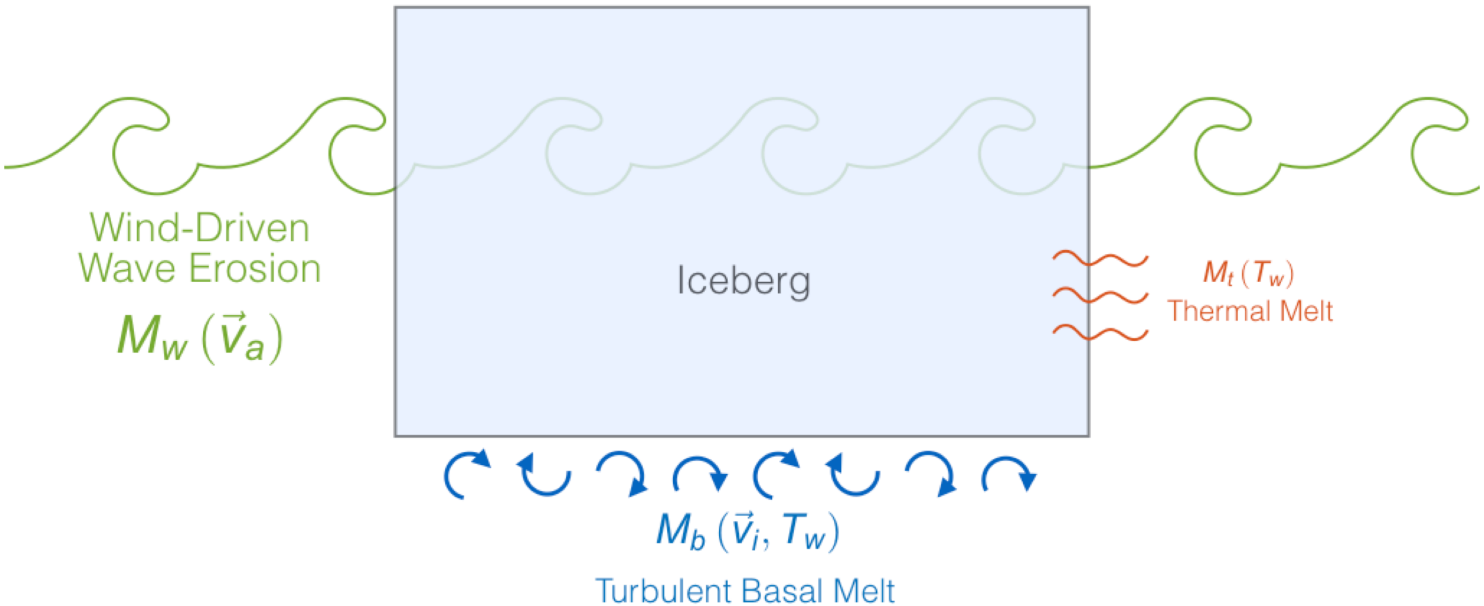
Iceberg decay model



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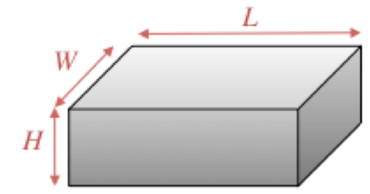


$$\frac{dL}{dt} = \frac{dW}{dt} = \underbrace{M_e}_{\text{wave erosion}} + \underbrace{M_v}_{\text{side melt}}$$

$$M_e = \tfrac{1}{12}\left(1 + \cos[\pi A_i^3]\right)(T_w - T_0)\, S(|\vec{v}_a|)$$

$$M_v = b_1\, T_w + b_2\, T_w^2$$

$$\frac{dH}{dt} = \underbrace{M_b}_{\text{basal melt}}$$

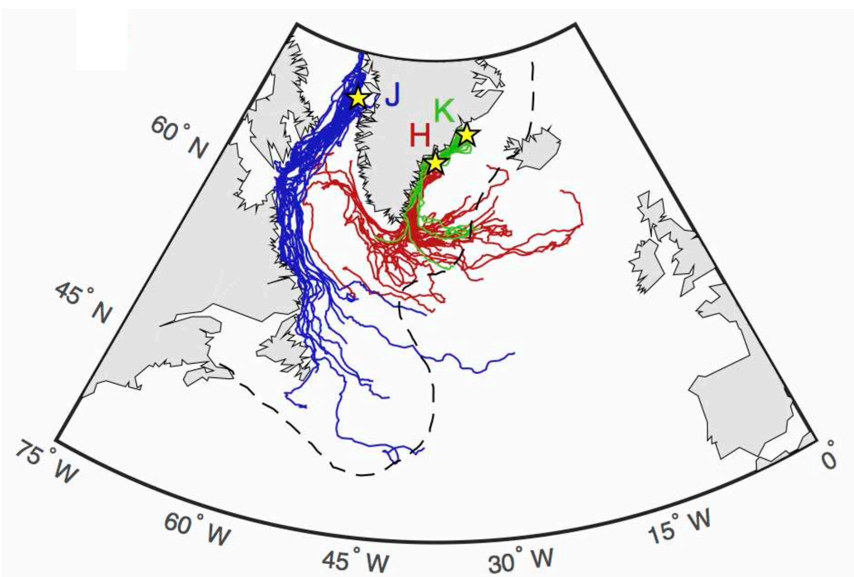
$$M_b = c\, |\vec{v}_w - \vec{v}_i|^{4/5}\, (T_w - T_i) L^{-1/5}$$

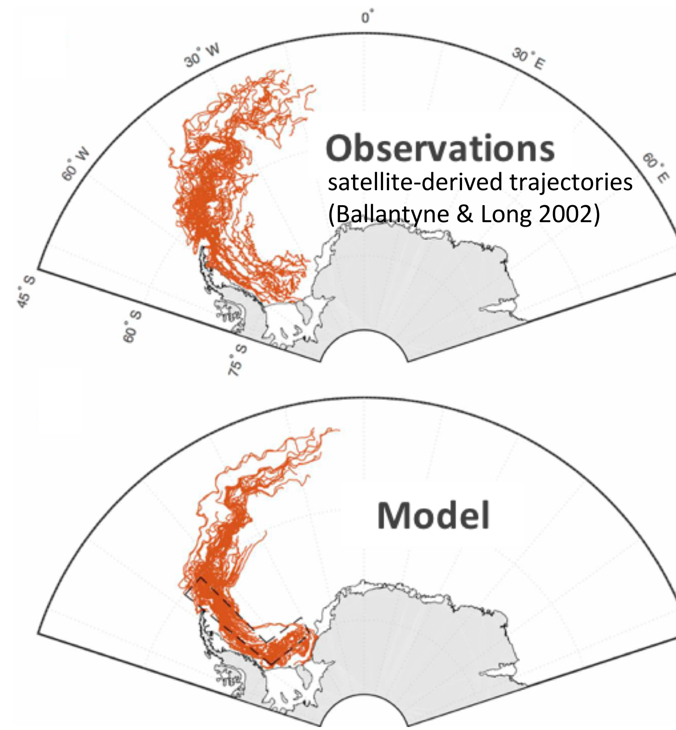
(Bigg et al. 1997)

Model validation

• Simulate non-interactive individual icebergs using observational estimate of v_a, v_w, & T_w (from ECCO2), with empirically-based seeding locations and initial iceberg size distributions (L is 100-1500m in NH and 15km-20km in SH).

• Qualitative agreement with region of observed icebergs in NH and distribution of satellite-derived trajectories in SH.





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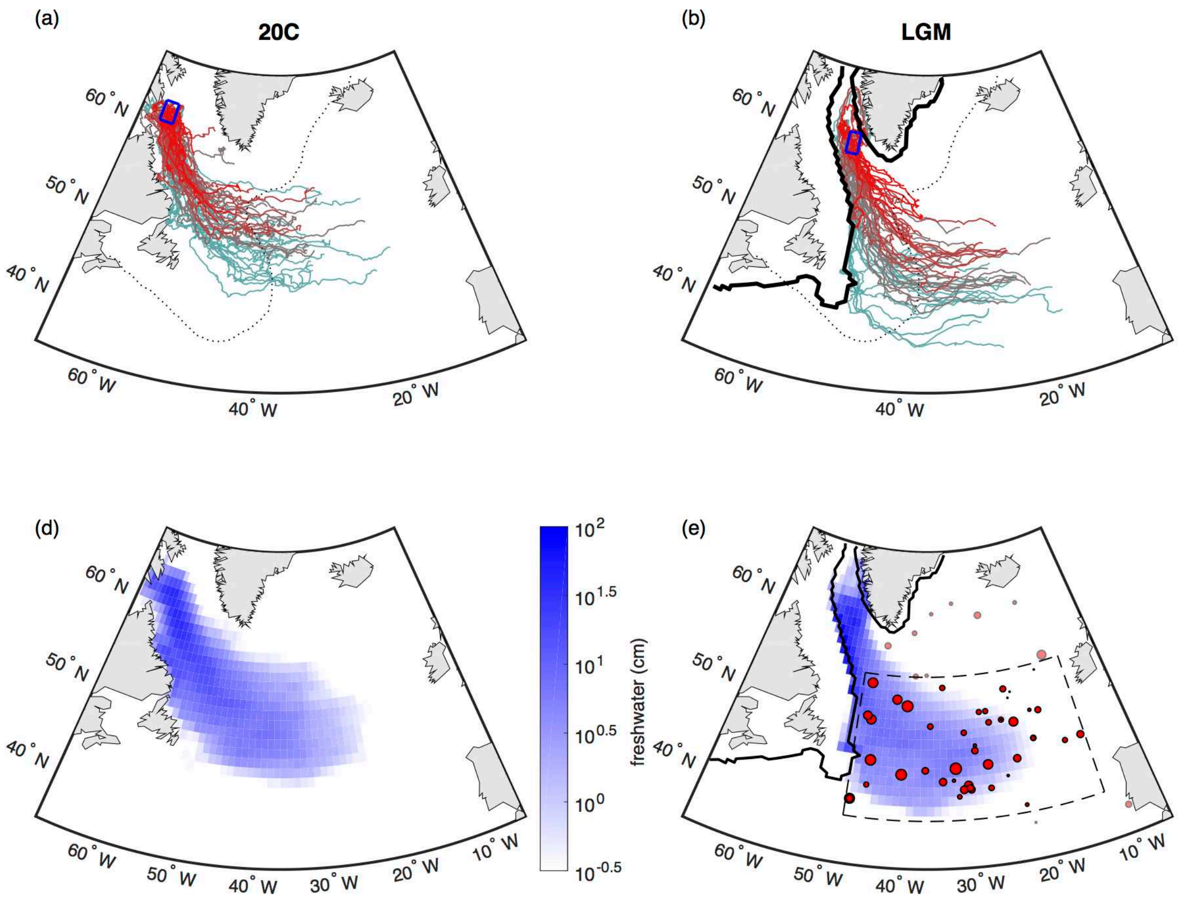
Simulated modern vs glacial icebergs

- Use CCSM4 coupled GCM simulation of LGM climate (Brady et al. 2013) for v_a, v_w, & T_w.



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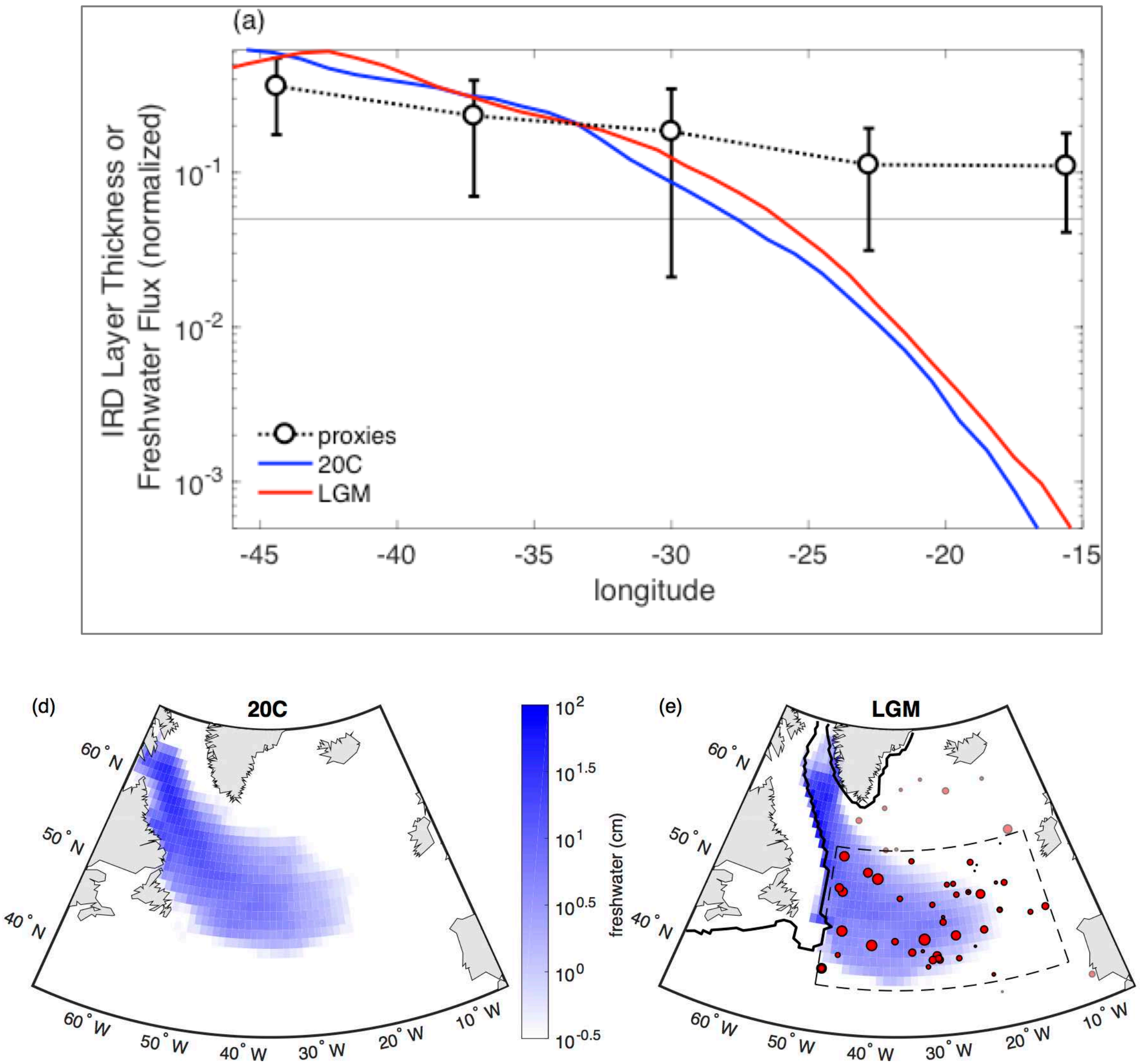

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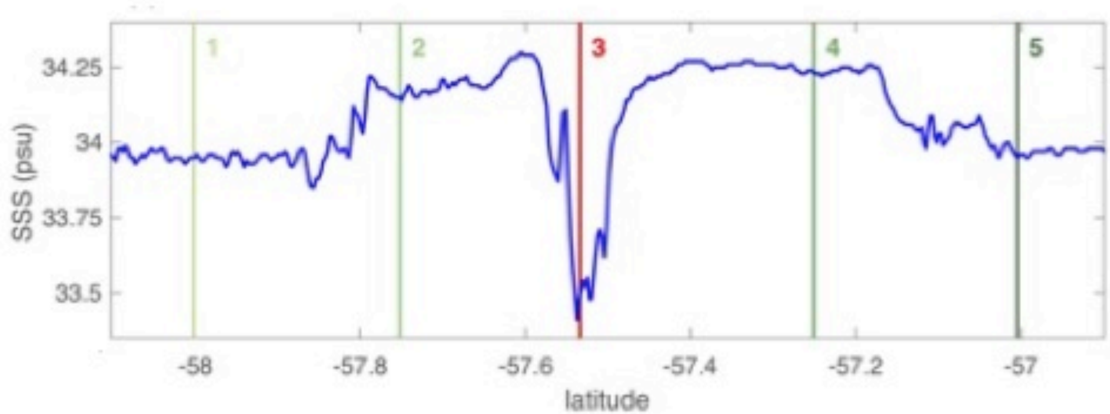
Inhibition of wave erosion by sea ice

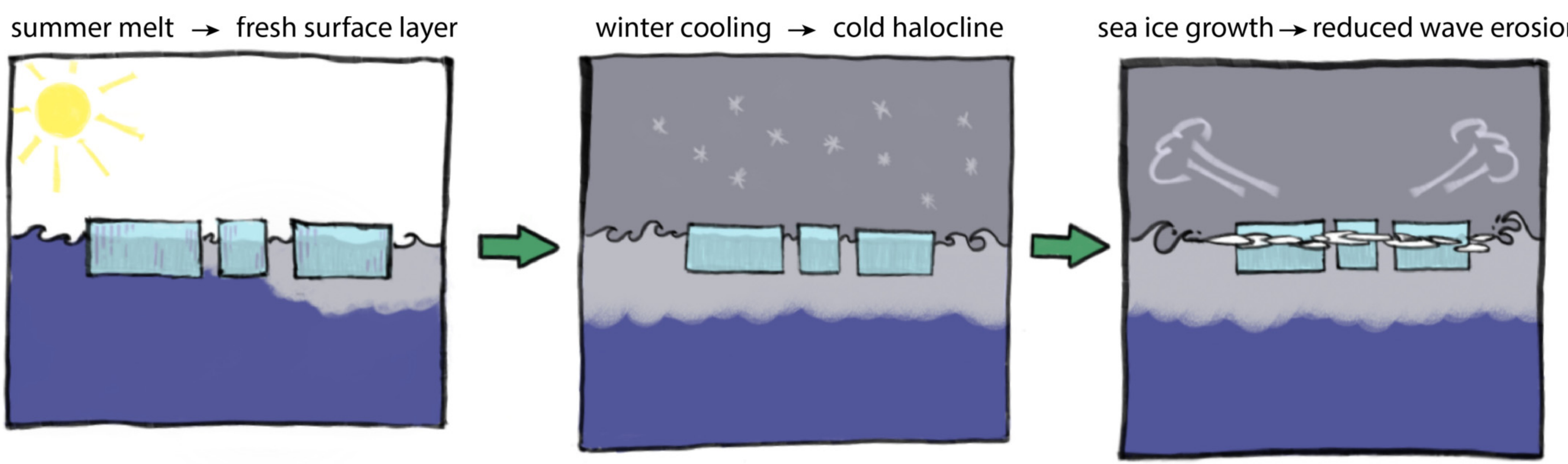
- Iceberg **meltwater** normally **spreads** horizontally over 10s of km.



Observed small iceberg cluster far from sea ice edge in Southern Ocean

Inhibition of wave erosion by sea ice

- Iceberg **meltwater** normally **spreads** horizontally over 10s of km.
- With icebergs **concentrated over scales larger than this**, sfc freshwater accumulates.
- Surface waters cool in fall but do not sink below this **halocline**: **sea ice forms**.
- Wintertime sea ice cover **inhibits wave erosion**, nearly turning off iceberg decay.



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⇒ The icebergs would create their own microclimate, analogous to the **mélanges** that form in Greenland Fjords (cf. Sulak et al. 2017).


Mélange in Greenland fjord

Plausibility of sea ice formation

• Use estimated **iceberg discharge** plus **T & S profiles** in GCM-simulated glacial IRD belt.

• If **2 months of freshwater** flux is concentrated in 25% of 40°N-55°N Atlantic Ocean & in upper 10m of column: **halocline is sufficient to allow sea ice growth**.

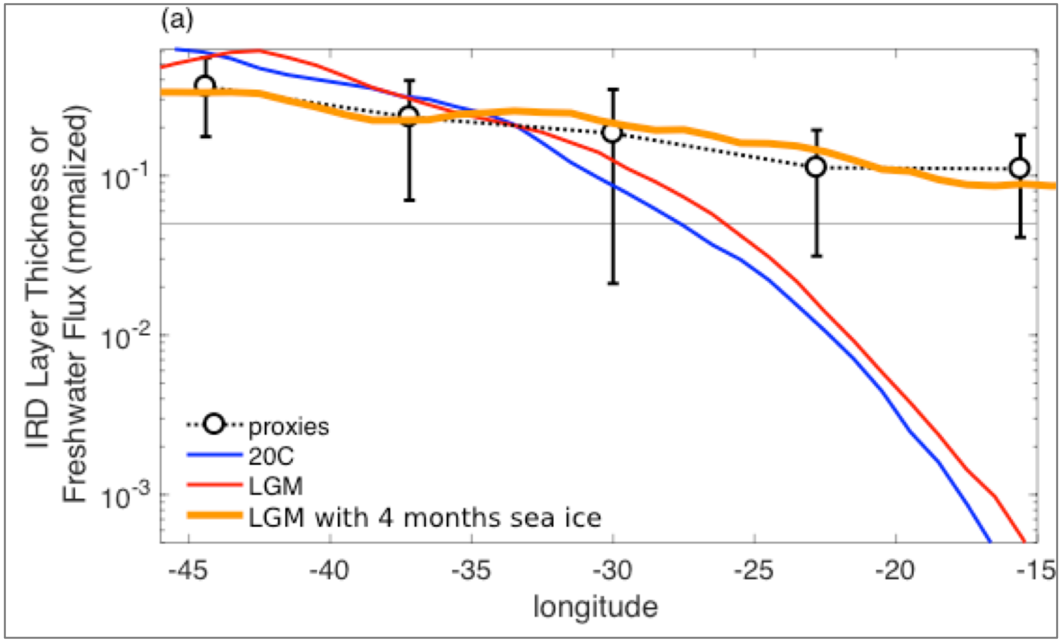
• This shallow halocline would substantially **reduce the effective surface heat capacity**.

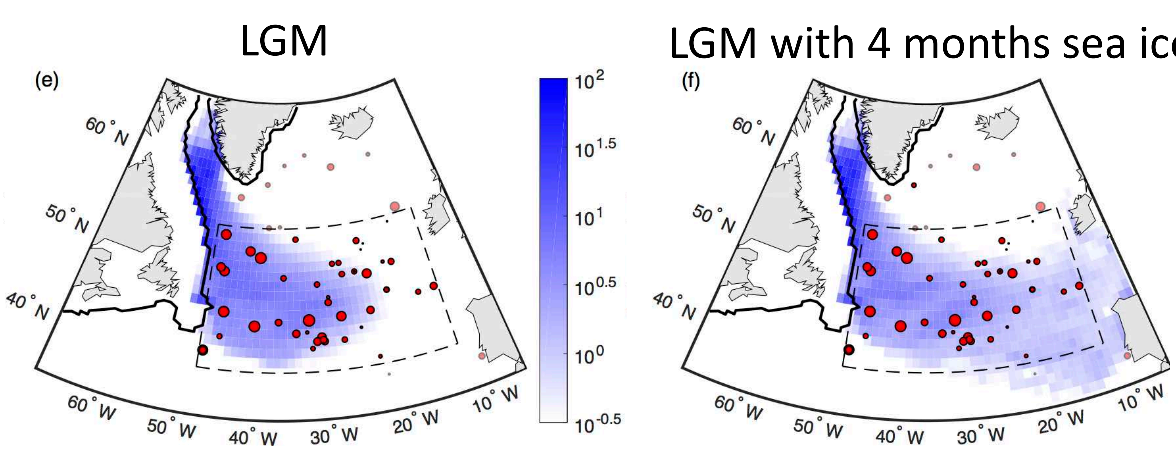
• We make the crude approximation that this would allow winter air temperatures to become **as cold as average over land** in 40°N-55°N.

• Assume sea ice coincides with air temperatures below –8°C, as in GCM.

⇒ This effect would allow **~4 months of sea ice** (Dec-Mar).

Influence of sea ice on icebergs





Summary

• Constructed an idealized analytical model of iceberg drift, and derived from physical principles the **empirical rule-of-thumb** that $\vec{v}_i = \vec{v}_w + 2\% \, \vec{v}_a$. Showed that this applies only for icebergs smaller than about 800m.

Wagner, Dell, Eisenman (*J. Phys. Oceanogr.*, 2017)

• Proposed a mechanism for the trans-Atlantic ice rafting of debris during Heinrich Events: **meltwater from icebergs during summer ⇒ halocline ⇒ winter sea ice ⇒ reduced wave erosion of icebergs during winter** *(only works when icebergs are densely packed over 10s of km).*

Wagner, Dell, Eisenman, Keeling, Severinghaus (*Earth Planet. Sci. Lett.*, in press)

(Model code at http://eisenman.ucsd.edu)