

Arctic Ocean tidal regime change across the Bolling-Allerod onset

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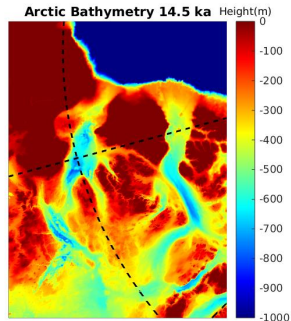
1 Introduction

2 Model

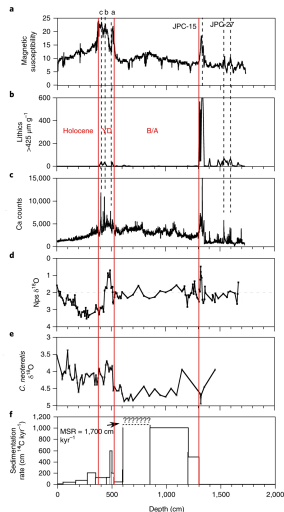
3 Results

4 Conclusion

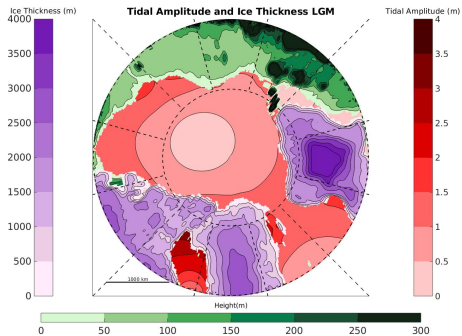
- Amundsen Gulf and McClure ice streams have retrograde bathymetry
- Lithic fragments found in Beaufort Sea ^[1]
- Possible second example of tidally triggered marine ice stream instability other than Heinrich Events ^[2]

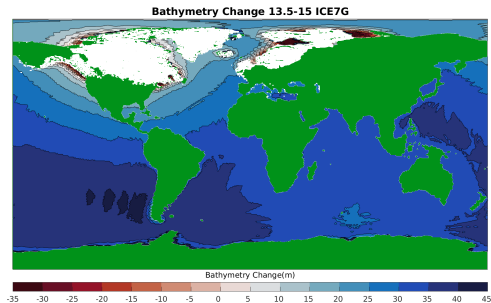


- Keigwin et al. 2018^[1] Found two IRD layers in the Beaufort Sea
- Later, weaker layer associated with YD
- Earlier, stronger layer occurring at approx 14.6 ka
- Potentially deposited during BA deglaciation of Amundsen Gulf



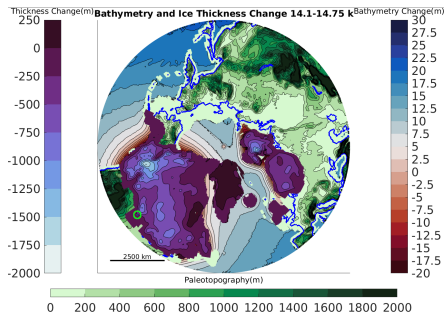
- Previously known that M2 Tide in Arctic Ocean is large.^[3]
- Coastal deglaciations may cause tidal hot spots





- Bolling Allerod warming caused by resuscitation of the Atlantic Meridional Overturning Circulation after H1
- This warming could have begun the deglaciation of Arctic ice streams
- The melting of the Southern Laurentide and Barents sea ice sheet produces MWP1a





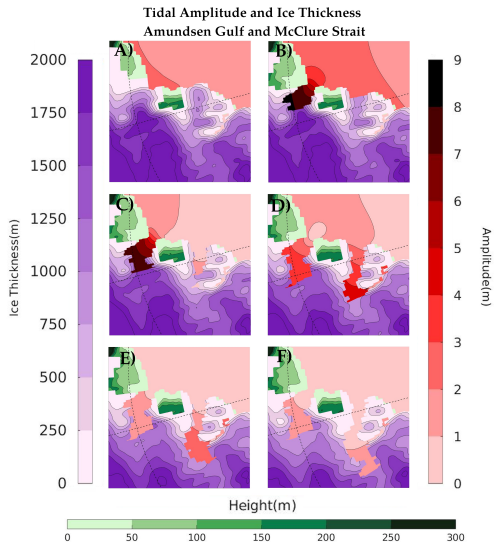
- MWP1a associated RSL rise, in combination with the altered Arctic coast line kills the M2 tidal amplitude
- Sea rise occurs unevenly over surface of the Earth
- RSL drop immediately offboard Laurentide due to loss of gravitational attraction from ice sheet

–	Barbados (m)	Tahiti (m)	Sunda Shelf (m)
Laurentide	14.3	21.3	17.3
Fenno-Scandian	2.1	2.1	1.9
Barents Sea	1.6	1.6	1.4
Greenland	0	0	0
Antarctica	1.4	0.7	0.6
Background	0.1	0	-0.1
Total	19.4	25.7	21.1
ICE-7G	18.6	25.6	21.3

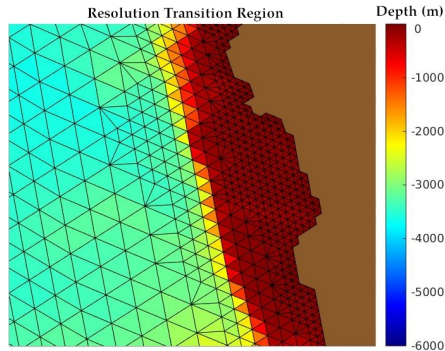
- Compared predicted RSL change in ICE-7G_NA (VM7)^[4, 5] to observations at Tahiti, Sunda Shelf and Barbados
- Isolated contributions from individual ice sheets, as well as Glacial Isostatic rebound
- Laurentide Ice sheet contribution larger at Sunda Shelf and Tahiti than at Barbados
- No need for increased Antarctic contribution



- We assumed an onset time of 14.6 kya^[1]
- 300-500 year duration
- Removed the ice from ICE-7G_NA (VM7)^[4, 5] in 3-5 equal 100 year steps
- Ran simulations with either and both straits assumed to deglaciate.



- Globally Unstructured Grids
- Discontinuous Galerkin Method
- Finite element method over piece-wise continuous trial functions
- Highly parallel



- Flux form of SWT equations:

$$\partial_t Q + \nabla \cdot F(Q) = S(Q), Q(x, y, t) = [\phi \ \phi u]^T$$

- Forcing:

$$F^x = \begin{bmatrix} \phi u \\ \phi u^2 + \frac{1}{2} \phi^2 \\ \phi uv \\ \phi uw \end{bmatrix}, F^y = \begin{bmatrix} \phi v \\ \phi uy \\ \phi v^2 + \frac{1}{2} \phi^2 \\ \phi vw \end{bmatrix}, F^z = \begin{bmatrix} \phi w \\ \phi uw \\ \phi vw \\ \phi w^2 + \frac{1}{2} \phi^2 \end{bmatrix}$$

- Source:

$$S = \left[0, -f \hat{e}_g \times (\phi u) + \phi \nabla (\phi_{eq} + \phi_{sal} - \phi_s) - \frac{g}{\rho} (D_{BL} + D_{IT}) \right]^T$$

- General Galerkin approach taken, but solution allowed to be discontinuous at boundaries through Lax-Friedrichs or Rusanov Flux.



- Solved the 2D spherical shallow water equations
- Self attraction and loading approximated as 0.085 g
- Boundary Layer dissipation parameterized as^[6]

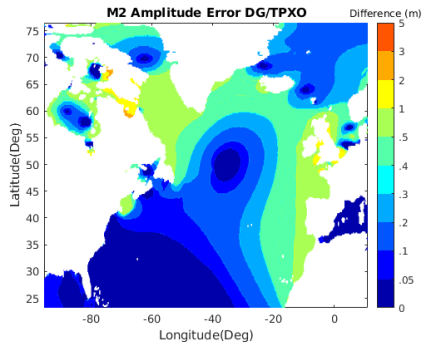
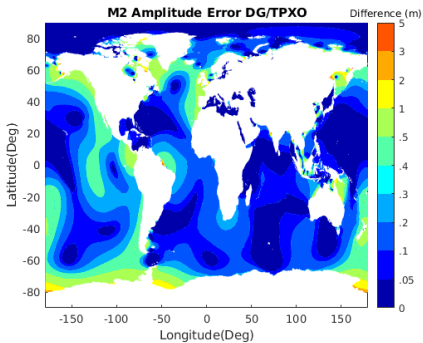
$$D_{BL} = \rho C_D u |u|, \quad C_D = 0.0025$$

- Internal tidal dissipation is modelled as^[7]

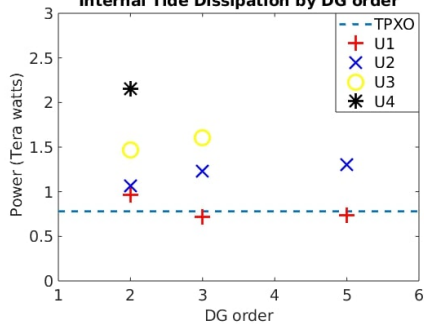
$$D_{IT} = \frac{\rho \bar{N}^2 h_s}{3\omega} (u \cdot \nabla h_s) \cdot \begin{cases} 1, & \text{for } |f| < \omega \\ 0, & \text{for } |f| > \omega \end{cases}$$

- Same model as that used in Salehipour *et al* (2013)^[8]

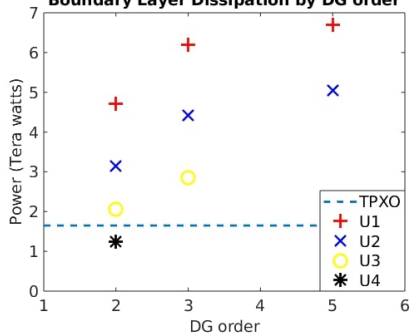


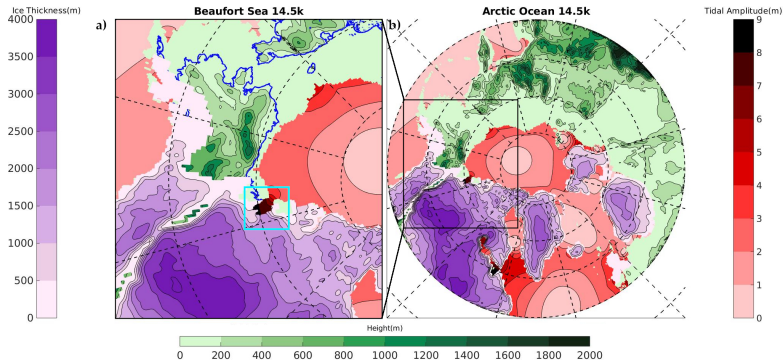


Internal Tide Dissipation by DG order



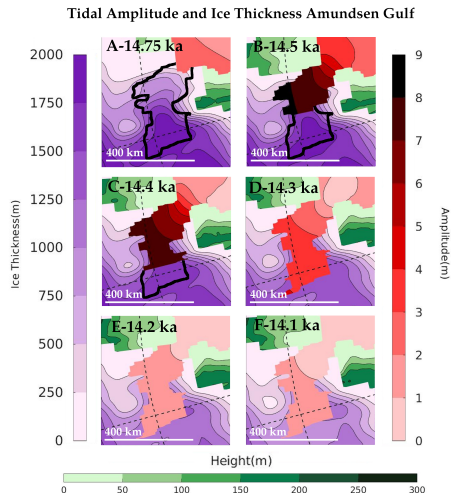
Boundary Layer Dissipation by DG order

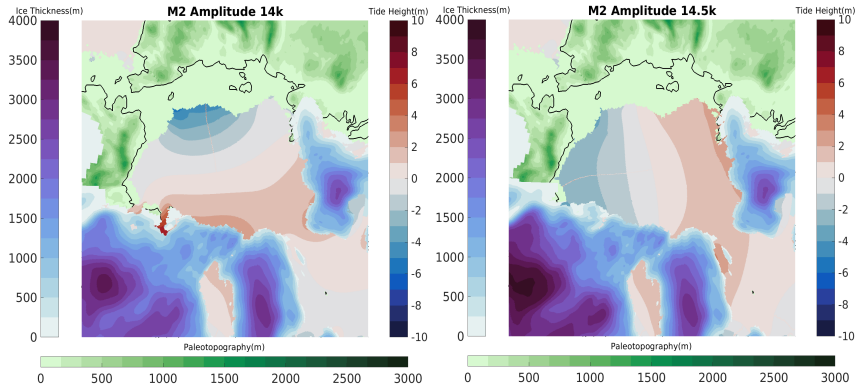




- M2 amplitude of 2-3 meters along most of Arctic coast
- As high as 4-5 meters in certain locations
- Amundsen Gulf has 3 meter tides prior to deglaciation
- McClure Strait doesn't have as high amplitude tides

- Continuous tidal forcing of Amundsen Gulf
- 9 meter M2 tidal amplitude initially
- Decreases to approximately a meter by 14.1 ka
- McClure Strait experiences 5 meter maximum tide





- Tidally Triggered Marine Ice sheet instability strongly implicated in Heinrich Events
- The Arctic Ocean was mega-tidal prior to Younger Dryas time
- Amundsen Gulf may be a second example of tidally triggered marine ice stream instability
- McClure Strait may also be amenable to tidally triggered instability
- Tidal triggering of ice streams may be a more important process than previously imagined



- Two ice streams have been identified, but are there more?
- Canadian Arctic Archipelago likely possibility
- Explicit modelling of tidal effects on grounding line movement
- Incorporation of rapid ice stream deglaciations into ice loading history



- [1] L. Keigwin, S. Klotsko, N. Zhao, B. Reilly, L. Giosan, and N. Driscoll, "Deglacial floods in the beaufort sea preceded younger dryas cooling," *Nature Geoscience*, vol. 11, no. 8, pp. 599–604, 2018.
- [2] J. Velay-Vitow, W. R. Peltier, and G. R. Stuhne, "The Tides of the Glacial Ocean and their Possible Connection to Heinrich Event Instabilities of the Laurentide Ice Sheet," *Journal of Geophysical Research: Oceans*, 2019.
- [3] S. D. Griffiths and W. Peltier, "Megatides in the Arctic Ocean under glacial conditions," *Geophysical Research Letters*, vol. 35, no. 8, 2008.
- [4] K. Roy and W. R. Peltier, "Space-geodetic and water level gauge constraints on continental uplift and tilting over North America: Regional convergence of the ICE-6G _C (VM5a/VM6) models," *Geophysical Journal International*, vol. 210, no. 2, pp. 1115–1142, 2017.
- [5] K. Roy and W. Peltier, "Relative sea level in the Western Mediterranean basin: a regional test of the ICE-7G_NA (VM7) model and a constraint on late Holocene Antarctic deglaciation," *Quaternary Science Reviews*, vol. 183, pp. 76–87, 2018.
- [6] G. I. Taylor, "I. Tidal friction in the Irish Sea," *Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character*, vol. 220, no. 571-581, pp. 1–33, 1920.
- [7] S. D. Griffiths and R. H. Grimshaw, "Internal tide generation at the continental shelf modeled using a modal decomposition: Two-dimensional results," *Journal of physical oceanography*, vol. 37, no. 3, pp. 428–451, 2007.
- [8] H. Salehipour, G. Stuhne, and W. R. Peltier, "A higher order discontinuous Galerkin, global shallow water model: global ocean tides and aquaplanet benchmarks," *Ocean Modelling*, vol. 69, pp. 93–107, 2013.

