Breaking the ice: what drove the deglaciation?

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The Last deglaciation

Progressive changes in:
- Orbit
- CO$_2$

Abrupt changes in:
- climate
- sea level (ice sheet retreat)

Reconstruction from Peltier (2004)

Ivanovic et al. (2016)
Outline

• Slow drivers of ice melt: Orbit and Greenhouse gases

• Fast sea level changes

• Impact of ice sheets on climate
Glimmer-CISM (Rutt et al., 2009)

- Shallow ice approximation of ice sheet dynamics
- mass balance scheme based on temperature and precipitation (positive degree day)
Simulating ice sheet evolution

Ice sheet model
Glimmer-CISM

General Circulation Models

Precipitation
Temperatures
Greenland Temperatures

- Transient simulations of the last deglaciation (last 21 kyr)
  - Greenhouse gases
  - Orbit
  - Ice sheet reconstruction
Deglaciation

Ice elevation (km)

Ice-5G extent

21 kyr BP
Decomposing role of forcings

Climate experiments with combinations of forcings:

- Fixed LGM climate
- ICE (ice sheets, orography, coastlines)
- ICE & GHG
- ICE & ORB (orbital forcing)
- ICE & GHG & ORB
- ICE & GHG & ORB & FWF (ice melt into ocean)

Decompose the effect of:

- ICE
- GHG
- ORB (orbital forcing)
- Interactions between forcings
North American ice volume loss due to:

- Orbit: 50%
- GHG: 30%
- Non-linearity due to positive feedbacks: +20%

Gregoire et al. GRL (2015)
Warming & sea level rise \(~14.6\) ka

**Warming:**
- \(~4-5\) °C in N. Hemisphere in a couple of centuries
- Cooling in S. hemisphere

**Sea level rise:**
12-22 m in \(<340\) years (global)
Meltwater Pulse 1a (MWP1a)

- What is the effect of the abrupt warming on North American ice sheet?
2 Transient simulation:
- FAMOUS (F-21k)
- CCSM3 (T-21k)
- Different freshwater forcing scenarios
- CCSM3 (T-21ka) experiment produced abrupt warming similar to Bølling ~14.7 ka

Liu et al. (2009)
Exploring uncertainty

- Different climate forcings:
  - FAMOUS ‘smooth’ climate change
  - CCSM3, abrupt warming (but cold high latitude bias)
  - CCSM3 abrupt warming + ‘anomaly’ bias correction

- Maxi-min Latin Hypercube Sampling:
  - 7 parameters (ice dynamics, mass balance)
  - 200 sets of parameter values

3D Latin Hypercube Sampling
Constraint on ice extent

• Assume 500 year standard deviation on radiocarbon age
  → Range of calendar years

• Compare map with the range of model time steps
  → Count the best match

Dyke (2004)
Ensembles of experiments

NROY: Not Ruled Out Yet (History Matching jargon)
Ice sheet evolution

FAMOUS absolute

CCSM3 anomaly

CCSM3 absolute

Saddle collapse

Abrupt warming

Gregoire et al., GRL (2016)
Sea level rise caused by abrupt warming

Saddle collapse just after abrupt warming

Gregoire et al., GRL (2016)
Sea level rise caused by abrupt warming

Elevation change (m) in 340 years following abrupt warming

→ Melt rate produced by the abrupt warming is $1/3^{rd}$ larger if warming triggers the saddle collapse

Gregoire et al., GRL (2016)
‘Saddle Collapse’ mechanism

W Cordillera

Laurentide E

Elevation (km)

11 kyr
11.6 kyr
11.7 kyr
11.8 kyr
12.2 kyr

200 km

19
Two possibilities

- Abrupt warming triggered saddle collapse (i.e. separation):
  - Contribution to MWP-1a sea level rise: **5-6 m in 340 years (up to 50%).**

- Ice sheets separated before the abrupt warming:
  - Ice sheet separation causes a small sea level change
  - Bølling abrupt warming produces **3-4 m in 340 year (up to 1/3rd contribution to MWP-1a)**
Impact on climate?

- Bi-polar see-saw pattern
- 600 year long Northern Hemisphere cooling
- Same duration as the meltwater pulse

Ivanovic et al., GRL (2017)

Central Greenland temperature
Buizert et al. (2014)

Timespan when the Saddle Collapse could have taken place
Other ice sheet instability mechanisms

Marine ice sheet instability

DeConto and Pollard, Nature (2016)
Reconstructing the retreat of the British ice sheet

Image from https://commons.lbl.gov/display/bisicles/BISICLES

Clark et al., Boreas (2017)
8.2 kyr cooling event

Greenland ice cores
(Thomas et al., QSR, 2007)

- Northern Hemisphere cooling.

Saddle collapse instability and the 8.2 kyr event

• Traditional hypothesis:
  • Outburst of Lake Agassiz and Ojibway (<2 years), possibly multiple events

• New hypothesis:
  • Collapse of North American ice sheet causing century-scale acceleration of meltwater flux

• Combined events?
  • Ice melt → 160 yr cooling
  • Lake outburst → 70 yr cooling

Gregoire et al., Nature (2012)
Climate response to ice sheet collapse

Matero et al. EPSL (2017)
Match amplitude and duration of the cooling event

Matero et al. (submitted)
Summary

- **Drivers of deglaciation:**
  - 50% Orbital forcing
  - 30% Greenhouse gases
  - + 20% feedbacks

- **Rapid sea level change caused by:**
  - Abrupt warming
  - Ice sheet instability

- **Acceleration in ice sheet melt causes changes in ocean circulation and climate:**
  - 8.2 kyr event could help “benchmark” the sensitivity of ocean circulation in climate models (...given enough data).
Mechanism for rapid sea level rise

- Separation of ice domes cause acceleration in melt rate: 7 m in 340 yr
- Separation occurred ~ time of MWP-1a (14.6 ka), a rapid sea level rise of 12-22 m in < 340 yrs.
- Can explain ~50% of sea level rise.