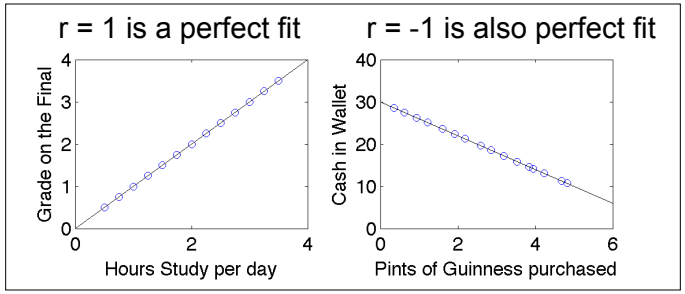
Tool: Correlation Coefficient (r)…

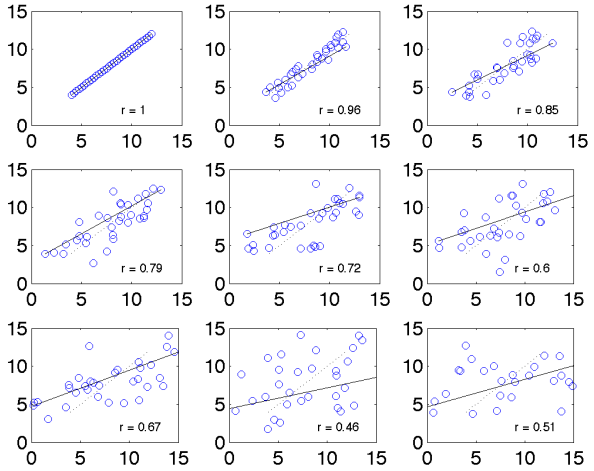
a measure of the goodness of a linear fit between two variables



r = 0 means there is no (linear) relationship between the variables

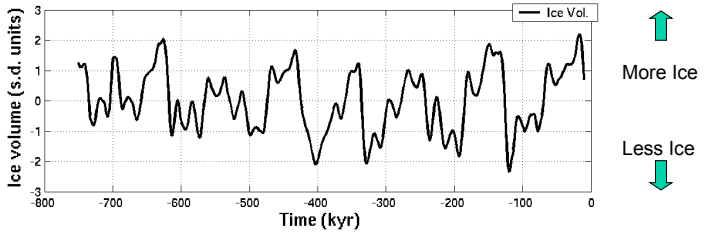
Tool: Correlation Coefficient (r)…

a measure of the goodness of a linear fit between two variables



| r | = 0.7 is an ok fit

The ice volume time series

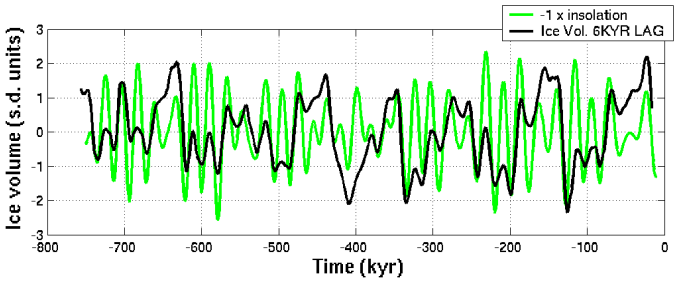


• the fraction of ^{18}O to ^{16}O in the shells of organisms preserved in deep sea sediment cores is proportional to ice volume

•Composite stack from ~ 20 sediment cores

Imbrie et al., 1984

Ice Sheet Growth versus High Latitude Solar

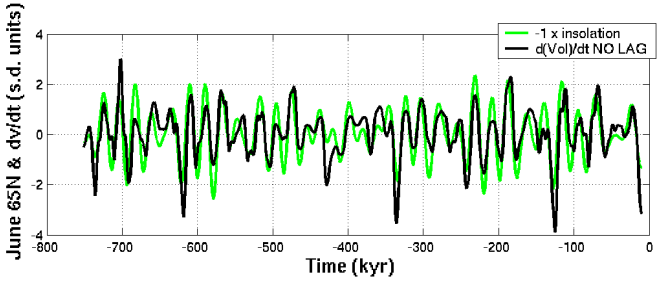


• **maximum correlation of -0.4**
with a 6 kyr lag of ice volume behind insolation
(e.g., low insolation is followed by increased ice)

• more ~100 kyr variability in ice volume than in insolation

Roe 2005

Ice Sheet Growth versus High Latitude Solar



June 65N Insolation (upside down)

Rate of Change of Global Ice Volume

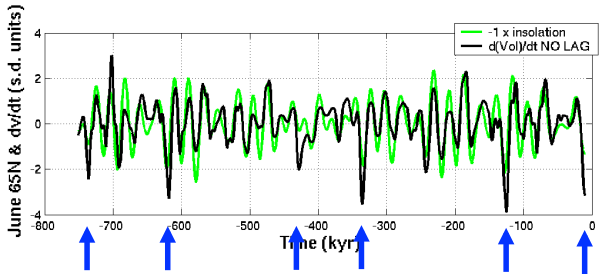
• *Rate of change of ice volume* is more directly related to high latitude NH summer insolation:

Correlation of -0.8 (at zero lag)

Roe 2005

Rate of change of ice volume

• Rate of change of ice volume more directly related to high latitude insolation



• Terminations coincide with insolation maxima - points to insolation trigger

• Major difference is large negative rates of ice change during major deglaciations

What do climate models say?

- Run a climate model (more later) using modern day forcing:
  - 360 ppm CO_2, today's insolation, today's land ice distribution, etc.
- Run a climate model using forcing associated with the Last Glacial Maximum (about 23 kyr ago):
  - 200 ppm CO_2, insolation and land ice distribution for 23kyr BP, etc.
- Take the difference (annual averaged over many years)

Surface Air Temperature: LGM minus Today

One Climate Model

Broccoli 2000

TABLE 2. Annually averaged surface air temperature difference (K) l

	Global	Northern Hemisphere	Southern Hemisphere
Land and ocean	−4.0	−5.9	−2.1
Land only	−6.4	−7.0	−3.4
Ocean only	−2.7	−4.1	−1.8

Second Climate Model

Hewitt & Mitchell 1997

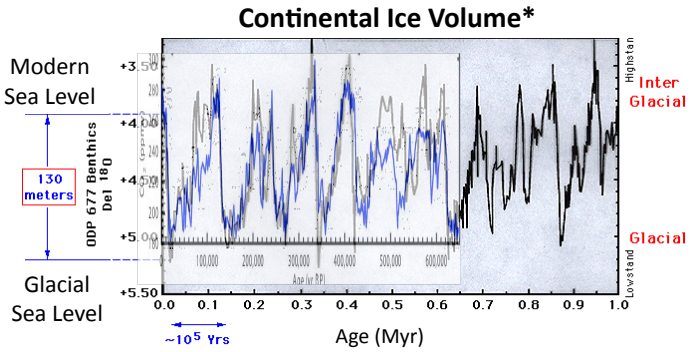
		Globe	N.Hemis	S.Hemis
Total	(simulated)	− 4.4	− 6.5	− 2.3
Topography and surface albedo	(simulated)	− 3.0	− 5.0	− 1.1
CO_2	(estimated)	− 1.4	− 1.6	− 1.2
Insolation	(simulated)	− 0.1	0.1	− 0.2
Total of rows 2, 3, 4		− 4.5	− 6.5	− 2.5

Ice Age Cycles: Some big solved problems

- Current climate is not the only possible one for Earth
  - indeed, glacial conditions seem to be preferred for the past 2.7Myr
- The ice Age Cycles wax and wane due to changes in the way the Earth orbits the sun
  - Global climate and CO_2 are intimately intertwined, but CO_2 is acting as a feedback and not the driver of ice age cycles
- A change in global-mean surface temperature of about 4-5°C is a massive climate shift
- If the orbital parameter theory is right, small triggers can produce major climate changes under some conditions

The Ice Age Cycles: Some big unsolved questions

- Why is CO_2 so highly correlated with ice volume?



*Oxygen Isotope composition of benthic organisms preserved in ocean sediment cores

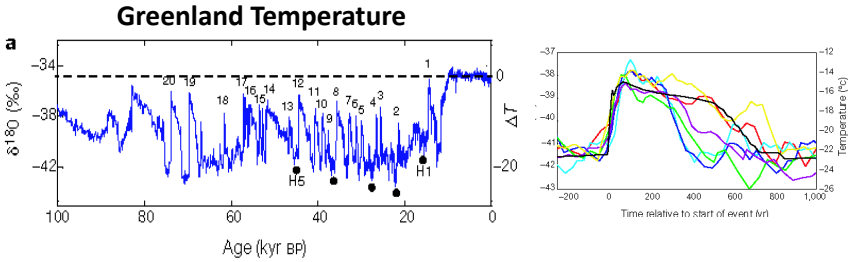
The Ice Age Cycles: Some big unsolved questions

- Why is CO_2 so highly correlated with ice volume?
  - Simple but incomplete answer: colder water can "hold" more CO_2
- Are changes in CO_2 important for the ice ages?
  - They provide a weak positive feedback in the NH
  - What about the SH? Temperature at Vostok is ~ in sync with NH ice volume. But is ice volume in the southern hemisphere correlated with ice volume in the northern hemisphere throughout the ice ages? Unknown
- What causes the major deglaciations?
  - Much more ice is lost in the terminations of an ice age than would be expected by simple increases in summer insolation.
  - Answer: ideas are on the table, but the jury is still out

Abrupt Climate Change during the Last Glacial Period

During Glacial stages, the climate system featured large rapid rearrangements.

Dansgaard/Oeschger (D/O) events show:



- Rapid onset of warming at Greenland (10°C in < 10 years!)
- Long-lived (~ 200 - 600 years) warm period, followed by slow decline back to cold conditions

What happens to climate when you have abrupt change in sea ice in the N. Atlantic?

- About 30 of these *abrupt* climate change events happened during the last ice age (one every ~1500 yrs)
- About two dozen are abrupt *warmings* due to abrupt removal of sea ice in the N. Atlantic
  - Sea ice usually extends south to about Maine/England in a glacial period
  - The abrupt warming is due to sea ice retreating northward into the Nordic Seas
- Five abrupt *coolings* also happened due to massive discharges from the Ice Sheet over N. America and Canada
  - Sea ice abruptly expands to cover most of the North Atlantic

Winter climate response to an abrupt increase in sea ice during the last glacial period

Change in Temperature

Change in Precipitation

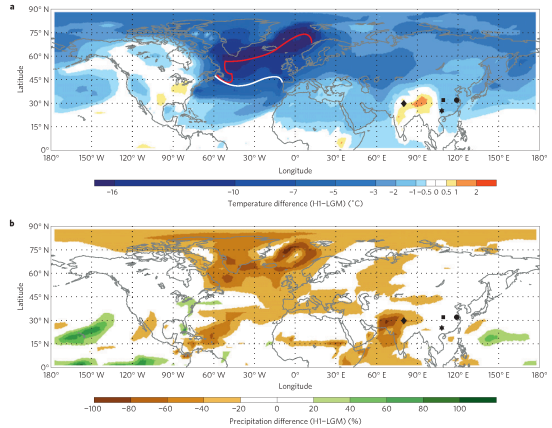
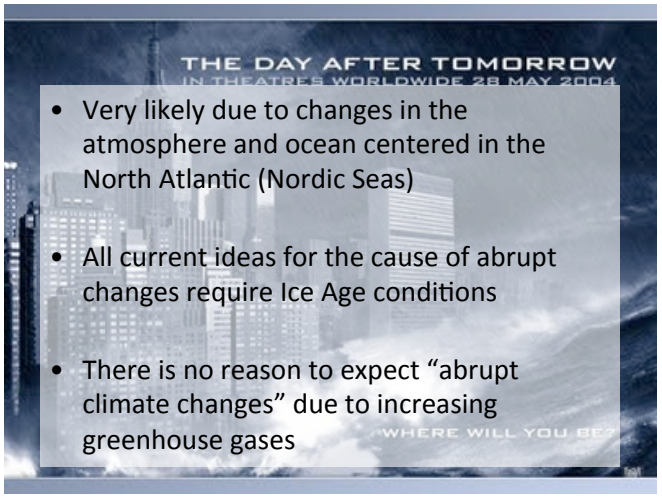


Figure 1 | Annual averaged temperature and precipitation difference between the H1 and LGM. a, Surface temperature difference (°C). **b**, Precipitation difference (%). Markers indicate the locations of the following caves: Hulu (circle), Songjia (square), Dongge (star) and Timta (diamond). The lines in **a** indicate the annual climatological 50% sea-ice extent for H1 (white) and LGM (red) in the North Atlantic sector.

Pausata et al 2010

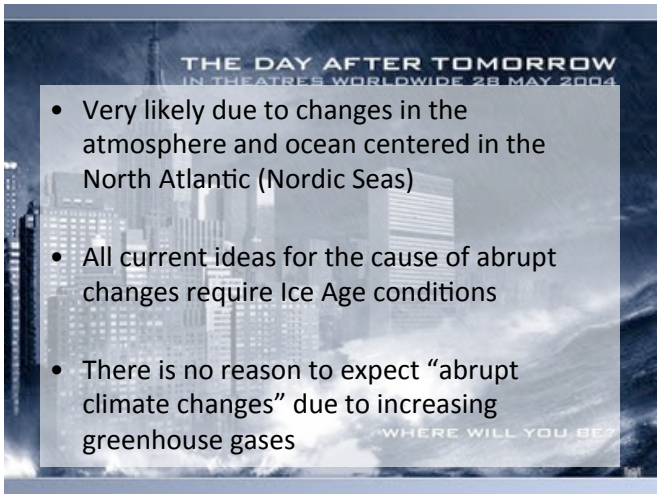
Abrupt Climate Change during the Last Glacial Period



- Very likely due to changes in the atmosphere and ocean centered in the North Atlantic (Nordic Seas)
- All current ideas for the cause of abrupt changes require Ice Age conditions
- There is no reason to expect "abrupt climate changes" due to increasing greenhouse gases

http://www.youtube.com/watch?v=SnvqsWVIuCE

Abrupt Climate Change during the Last Glacial Period



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