The role of the terrestrial biosphere in the glacial CO2 problem: Implications for future carbon-climate feedback

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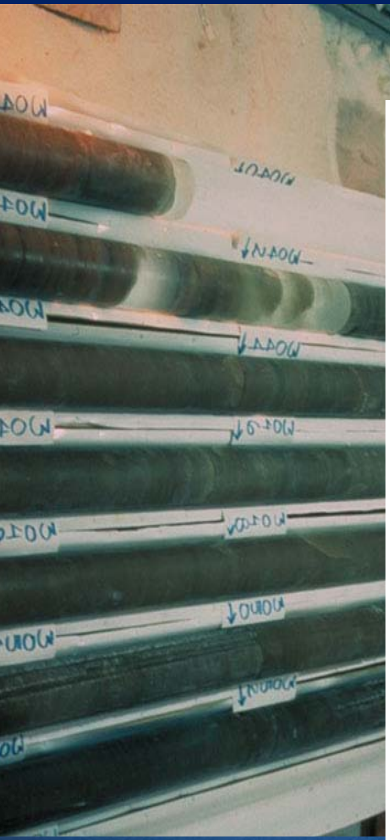
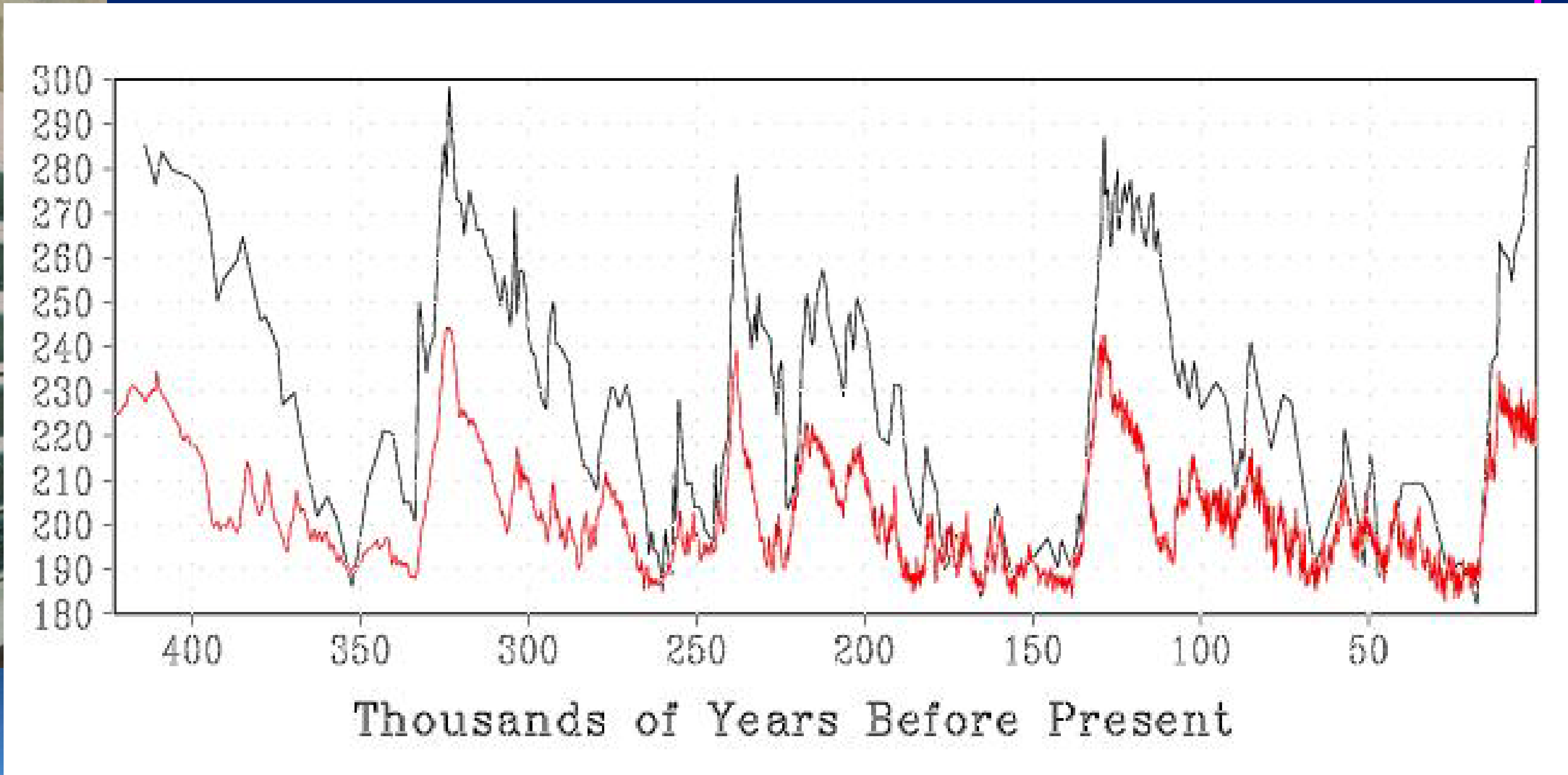
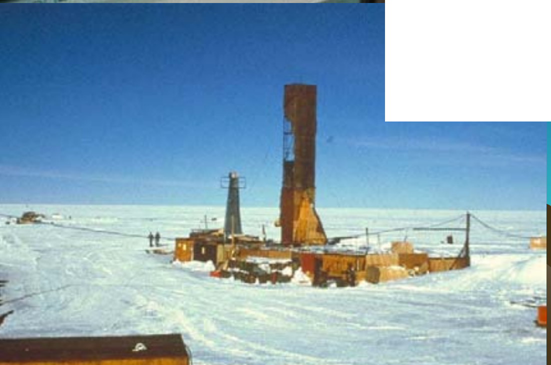
400 thousand years of Climate History

Strong correlation between CO_2 and temperature

Human







Ice core from Vostok, Antarctica

Where are we? CO2+Climate

...there is no consensus on what causes ice-age CO_2 changes. The sheer number of explanations for the 100,000-year cycle and for CO2 changes seem to have dulled the scientific community into a semi-permanent state of wariness about accepting any particular explanation. This places a great burden of proof on proponents of any particular theory.

T. Crowley (2002)

What caused lower glacial CO_2?

- Physical/chemical reorganization of the oceans
  - Temperature, salinity
  - Circulation
  - Sea ice in the southern oceans
- Carbonate chemistry
  - Deep ocean sediments
  - Coral reef
- Changes in biological productivity
  - The iron hypothesis

Land vs. Ocean in glacial-interglacial CO_2 change

Typical partitioning of deglacial CO2 change (Interglacial - Glacial):

- Atmosphere +180 Gt (increase)
- Land +500 Gt (increase)
- Ocean -680 Gt (decrease)

Marine C13	200-1000Gt
Pollen	430-1900Gt
Model	0-1000Gt

Traditional view: Land is an additional burden of about 30 ppmv that ocean carbon pool has to accommodate

We suggest: Glacial land carbon storage was larger, not smaller than interglacial, so that land carbon contributes to the CO2 change, thus helping the ocean scenarios. This idea challenges all the three methods of estimating glacial land carbon.

Role of Land

Three Methods of estimating land carbon storage at LGM

1. Marine C13 inference (Shackleton 1977)
2. Paleoecological data, i.e., pollen (Adams et al., 1990)
3. Terrestrial carbon model forced by reconstructed climate (Prentice and Fung 1990)

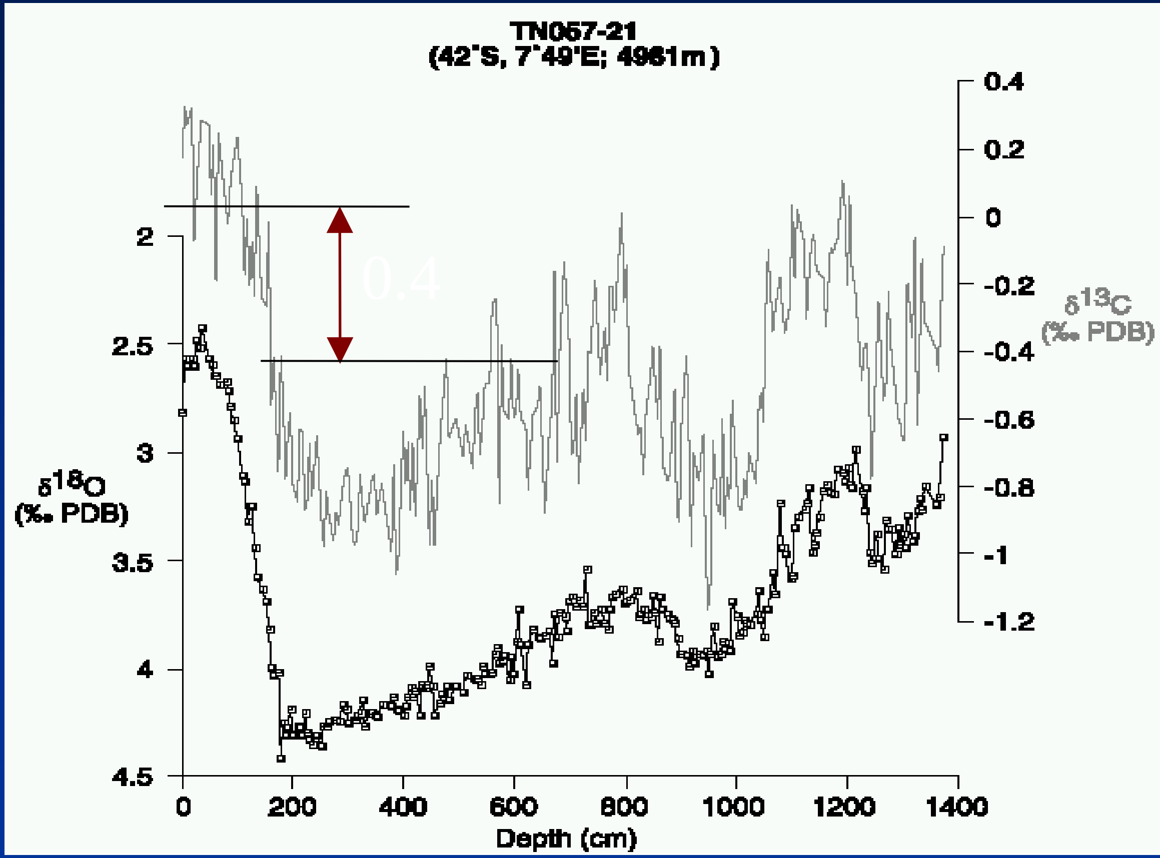
An example of marine C13 inference:

Present values (approx):

d13C(land) = -24‰

d13C(atmo)= -6‰

d13C(ocean)= 0 ‰



A 500Gt transfer of land carbon to the ocean implies a lowering of d13C(ocean) by 0.35‰ at LGM.

Challenge: the dC13 change has alternative explanations (Spero et al., 1997, Lea et al., 2000)

Paleoecological reconstruction

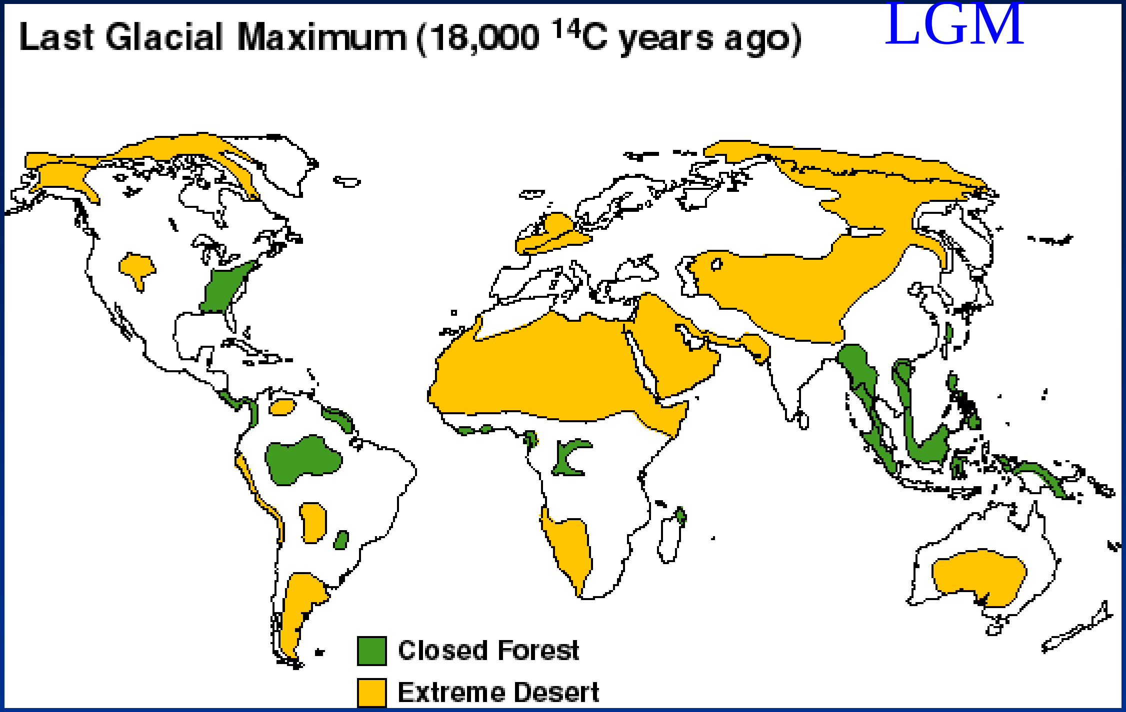
Major differences at LGM:

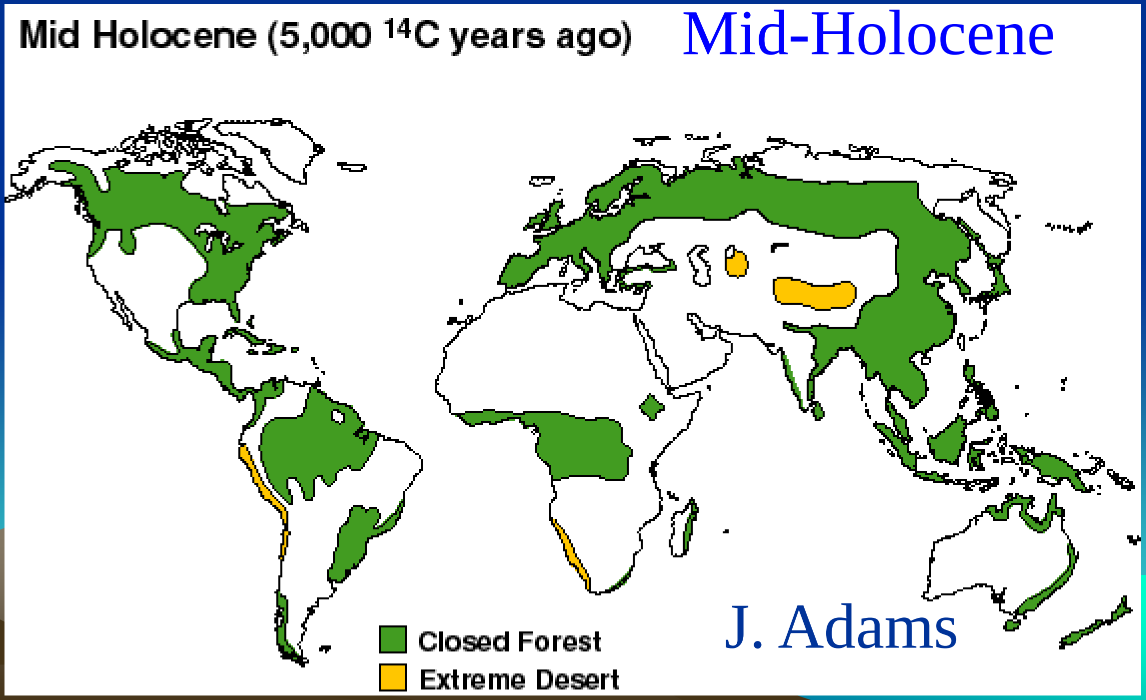
1. Climate drier/colder
2. CO2 level lower
3. Ice sheets 23M km2
   => less carbon on land

4. Continental shelf 18M km2
   => more carbon on land

Overall, much less carbon on land

Challenges:
1. The ‘modern analog’ approach may underestimate soil carbon storage which would be high at lower temperature
2. Nothing under ice?





Estimates of land carbon storage   Holocene - LGM

Source	Method	Land carbon difference
Shackleton, 1977	ocean δ^{13}C, 0.7 o/oo	1000
Duplessy et al., 1984	ocean δ^{13}C, 0.15 o/oo	220
Berger and Vincent, 1986	ocean δ^{13}C, 0.40 o/oo	570
Curry et al., 1988	ocean δ^{13}C, 0.46 o/oo	650
Duplessy et al., 1988	ocean δ^{13}C, 0.32 o/oo	450
Broecker and Peng, 1993	ocean δ^{13}C, 0.35 o/oo	425
Bird et al., 1994	ocean δ^{13}C	270-720
Maslin et al., 1995	ocean δ^{13}C 0.40+0.14 o/oo	400-1000 (700)
Beerling, 1999	13C inventory	550-680
Adams et al., 1990	palaeoecological data	1350
van Campo et al., 1993	palaeoecological data	430-930 (713)
Crowley et al., 1995	palaeoecological data	750-1050
Adams and Faure, 1998	palaeoecological data	900-1900 (1500)
Prentice and Fung, 1990	GISS, Holdridge/Carbon Density	-30 to 50
Friedlingstein et al., 1992	Sellers, SLAVE	300
Prentice et al., 1993	ECMWF T21, BIOME	300-700
Esser & Lauten. 1994	ECHAM, HRBM	-213 to 460
Friedlingstein et al., 1995	GISS/Sellers, SLAVE	507-717 (612)
Peng et al., 1995	Pollen Recon., OBM	470-1014
Francois et al., 1998	ECHAM2, CARAIB	134-606
Beerling, 1999	UGAMP/NCAR, SDGVM	535-801 (668)
Otto et al., 2002	4 PMIP models, CARAIB	828-1106
Kaplan et al., 2002	UM, LPJ	821
This study	CCM1, VEGAS	-407 to -749 (-547)

Marine C13: 270-1000Gt

Pollen: 430-1900

Model: -213 to 1106

Climate effects: Temperature, precipitation and CO2 fertilization

- Temperature: Lower decomposition rate leads to higher soil storage, especially soil
- Precipitation: Slightly drier with regional difference; overall effect small
- CO2 fertilization: High sensitivity; without CO2 fertilization effect, models tend to produce a higher storage at LGM (Kaplan et al. 2002; Otto et al. 2002)

Challenge: How good are model parameterizations?

Summary of estimates of land carbon change

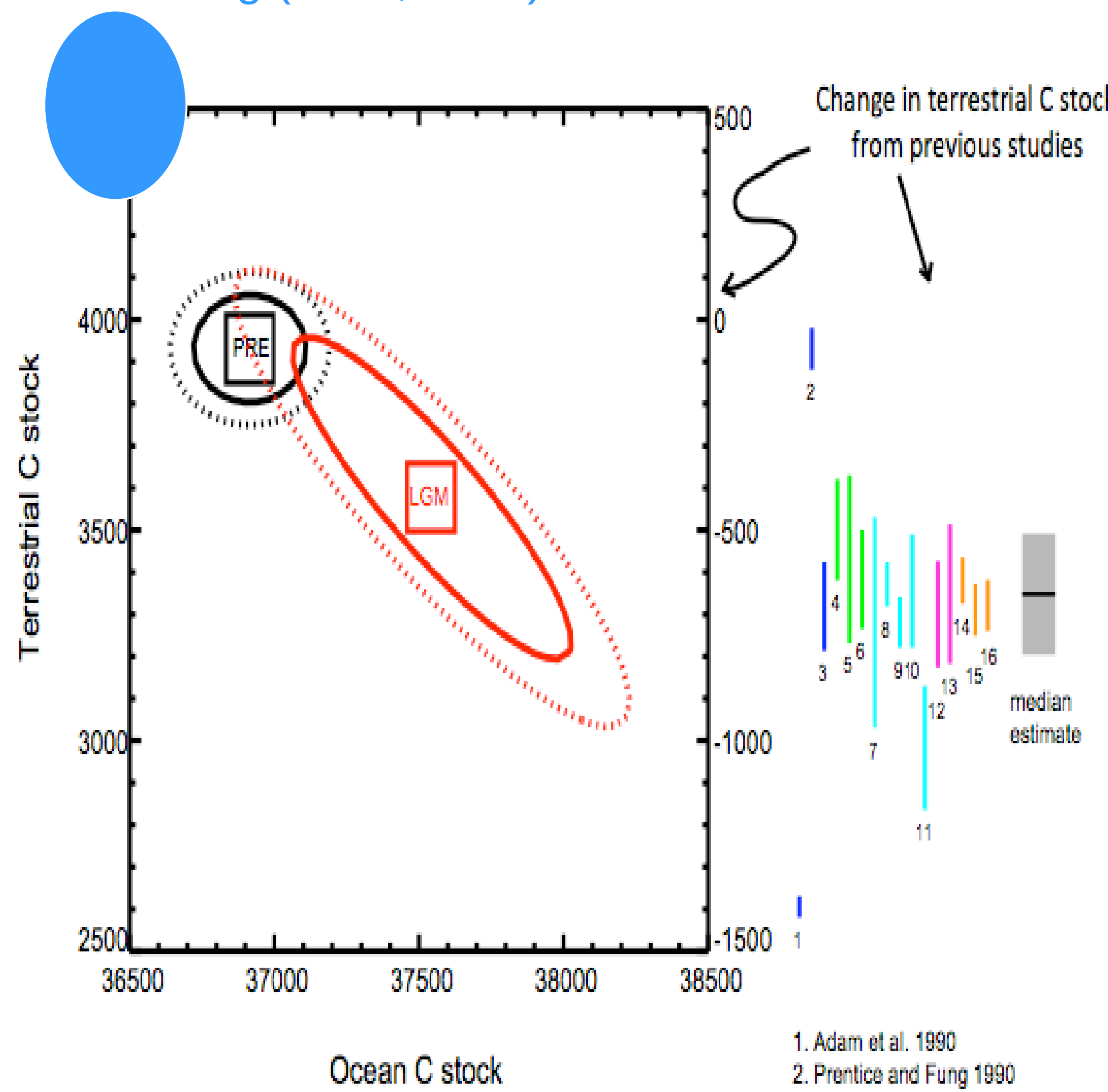
LGM-Holocene

Marine C13

Pollen

Model

Zeng (2003, 2007)



Ciais et al. 2010

1. Adam et al. 1990
2. Prentice and Fung 1990
3. Friedlingstein et al. 1992
4. Bird et al. 1994
5. Bird et al. 1996
6. Street-Perrott et al. 1998
7. Prentice and Sykes 1995
8. Friedlingstein et al. 1995
9. Francois et al. 1998
10. Francois et al. 1999

The Glacial Burial Hypothesis I

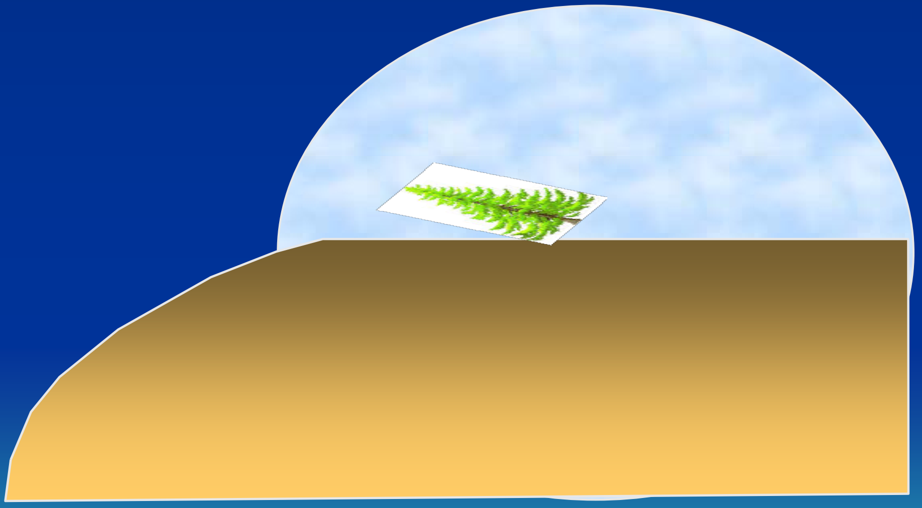
The development of these huge ice sheets must have led to the destruction of all organic life at the Earth's surface. The ground of Europe, previously covered with tropical vegetation and inhabited by herds of great elephants, enormous hippopotami, and gigantic carnivora became suddenly buried under a vast expanse of ice covering plains, ... The silence of death followed...

Louis Agassiz (circa 1837)

What happens to boreal carbon during glaciation?

Bulldozer vs. Freezer

The Bulldozer hypothesis



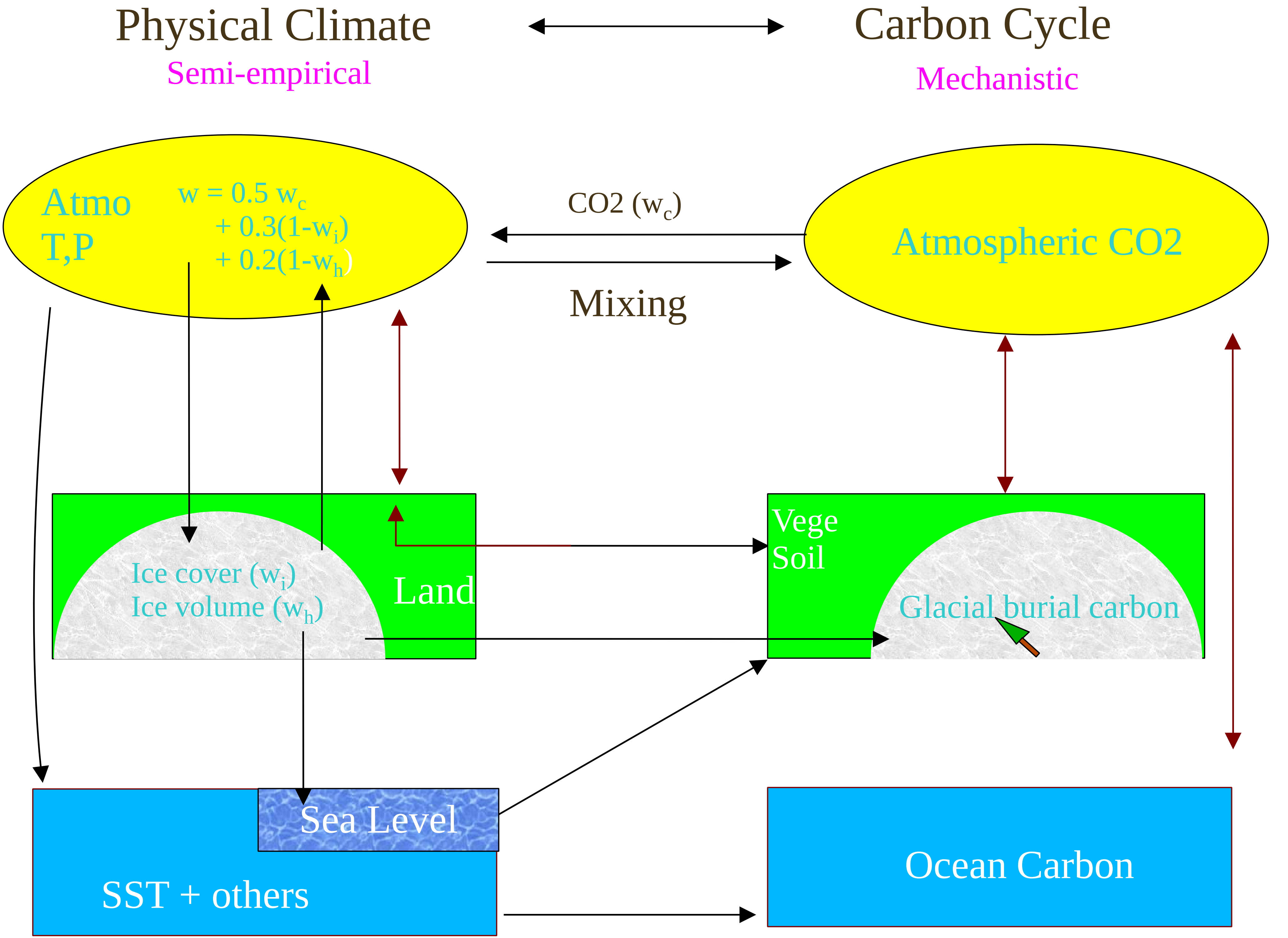
The glacial burial hypothesis

Can buried carbon be preserved? GBH II

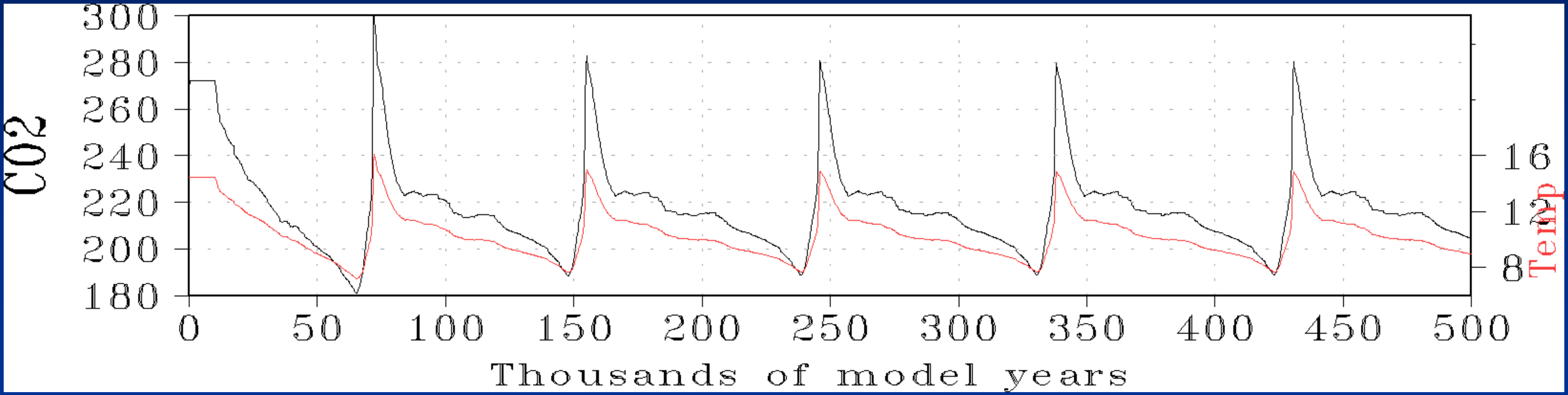
Pine needle or grass blade
under the Greenland icesheet

Woody debris, Malaspina Glacier, Alaska

Oetzi the iceman, 5300yrs old,
The Alps, Italian-Austrian border


Physical Climate
Semi-empirical
Carbon Cycle
Mechanistic
Atmo
T,P
w = 0.5 w_c
+ 0.3(1-w_i)
+ 0.2(1-w_h)
CO2 (w_c)
Mixing
Atmospheric CO2
Ice cover (w_i)
Ice volume (w_h)
Land
Vege
Soil
Glacial burial carbon
Sea Level
SST + others
Ocean Carbon

500 ky simulation from the coupled carbon-climate model

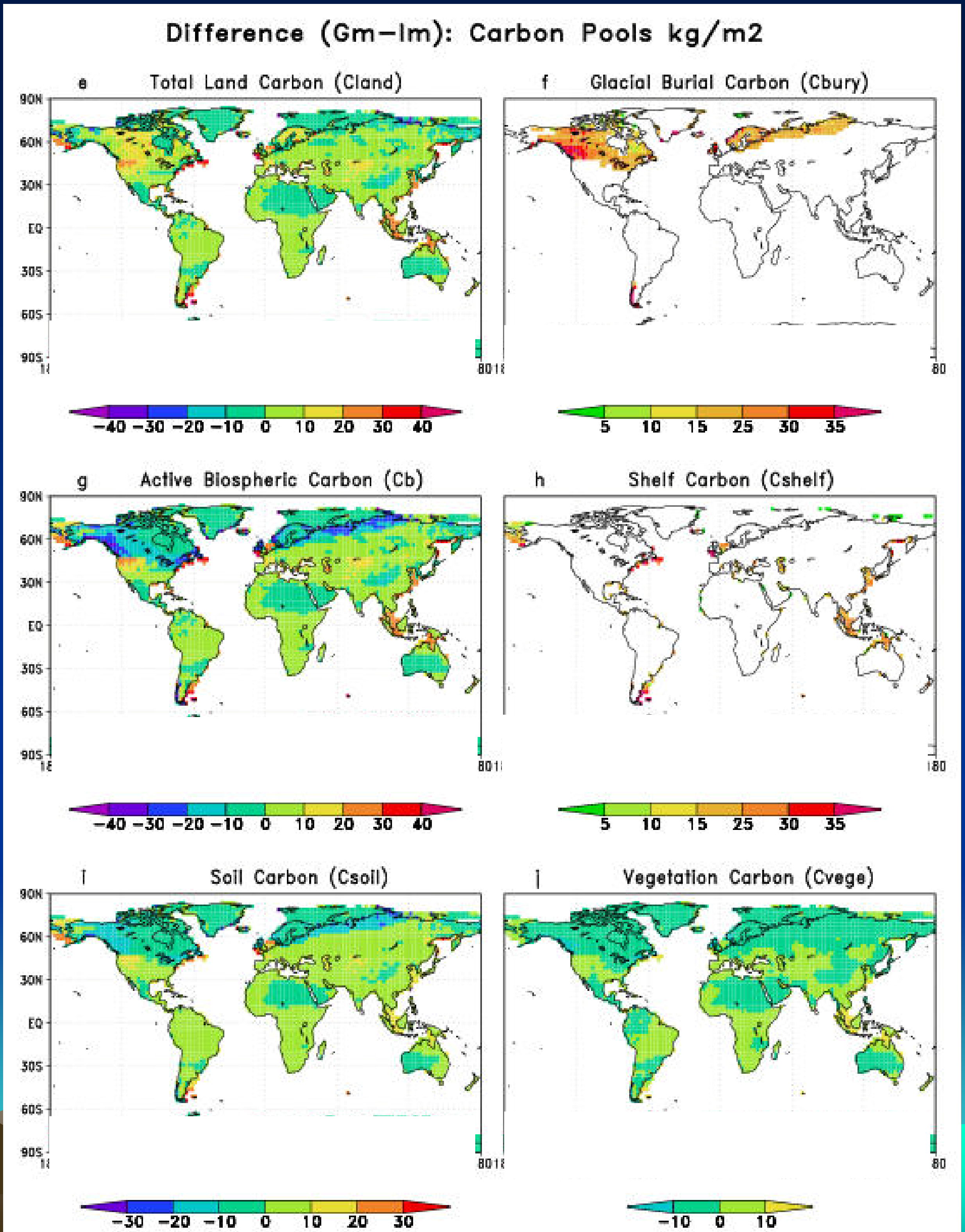


Model:
semi-empirical physical climate and icesheet; state-of-the-art carbon cycle

No orbital forcing

Initialization: interglacial equilibrium
First 26ky: an artificial CO_2 sink of 0.015GtC/y (390GtC)
After 26ky: no external forcing;
After 150ky: settled to quasi-100ky cycles, $\Delta T=6\ ^{o}C$

Difference in carbon pools
Glacial max – Interglacial



Major changes:

Glacial burial carbon
Continental shelves
Active biosphere
due to lowered temperature

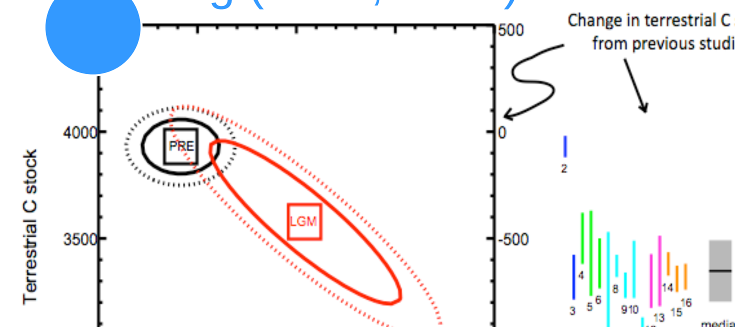
Why do our results on terrestrial carbon change differ from others?

1. The inclusion of about 500Gt carbon buried under the ice sheets (the glacial burial hypothesis);
   Not considered in the past

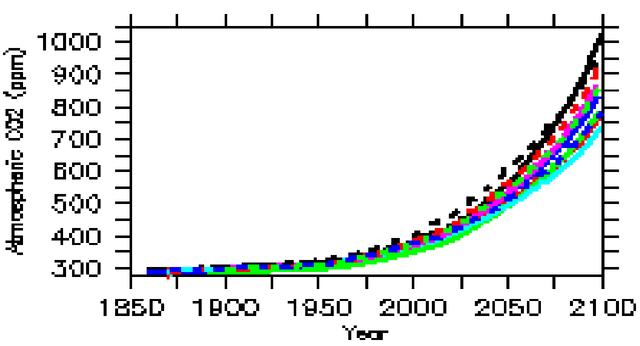
2. The delayed regrowth (soil/nutrient development) in the formerly ice covered regions (the importance of transient consideration, together with the multiple time scales in the ocean and sediments); Not considered before

3. More carbon storage at Gm in non-ice covered regions due to the reduced decomposition rate of soil carbon at lowered temperature, which outcompetes the more modest effects of reduced precipitation and CO_2 fertilization (colder but not too much drier, weaker CO_2 fertilization)
   Uncertainty

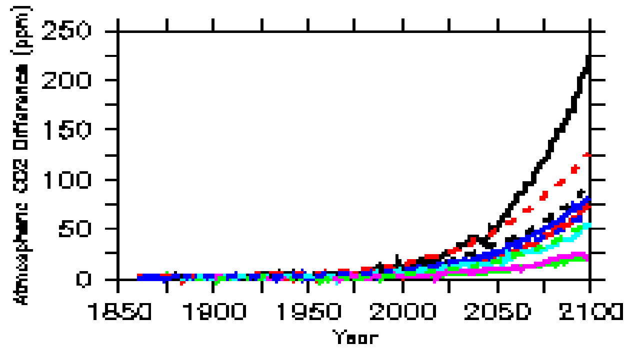
Zeng (2003, 2007)



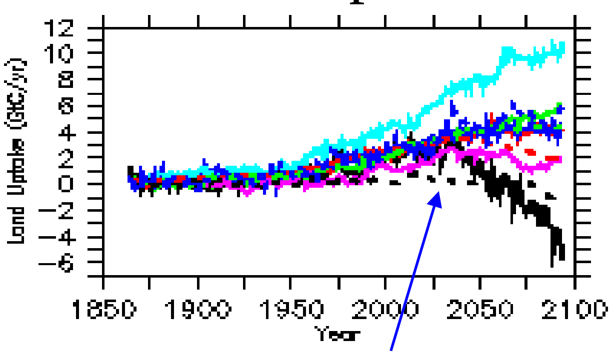
CO2



ΔCO2 from climate feedback

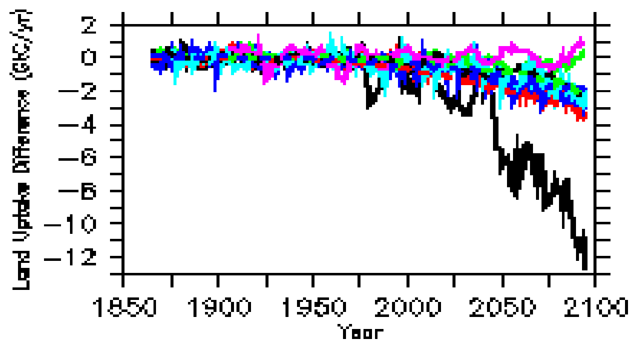


Land uptake

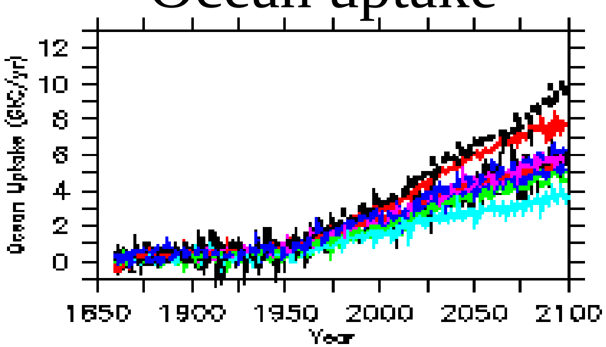


UMD model

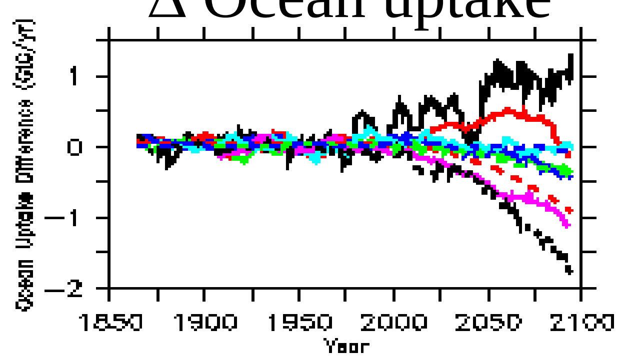
Δ Land uptake



Ocean uptake



Δ Ocean uptake



Friedlingstein et al., 2006

Enhanced global warming from carbon-climate interaction: the C4MIP results

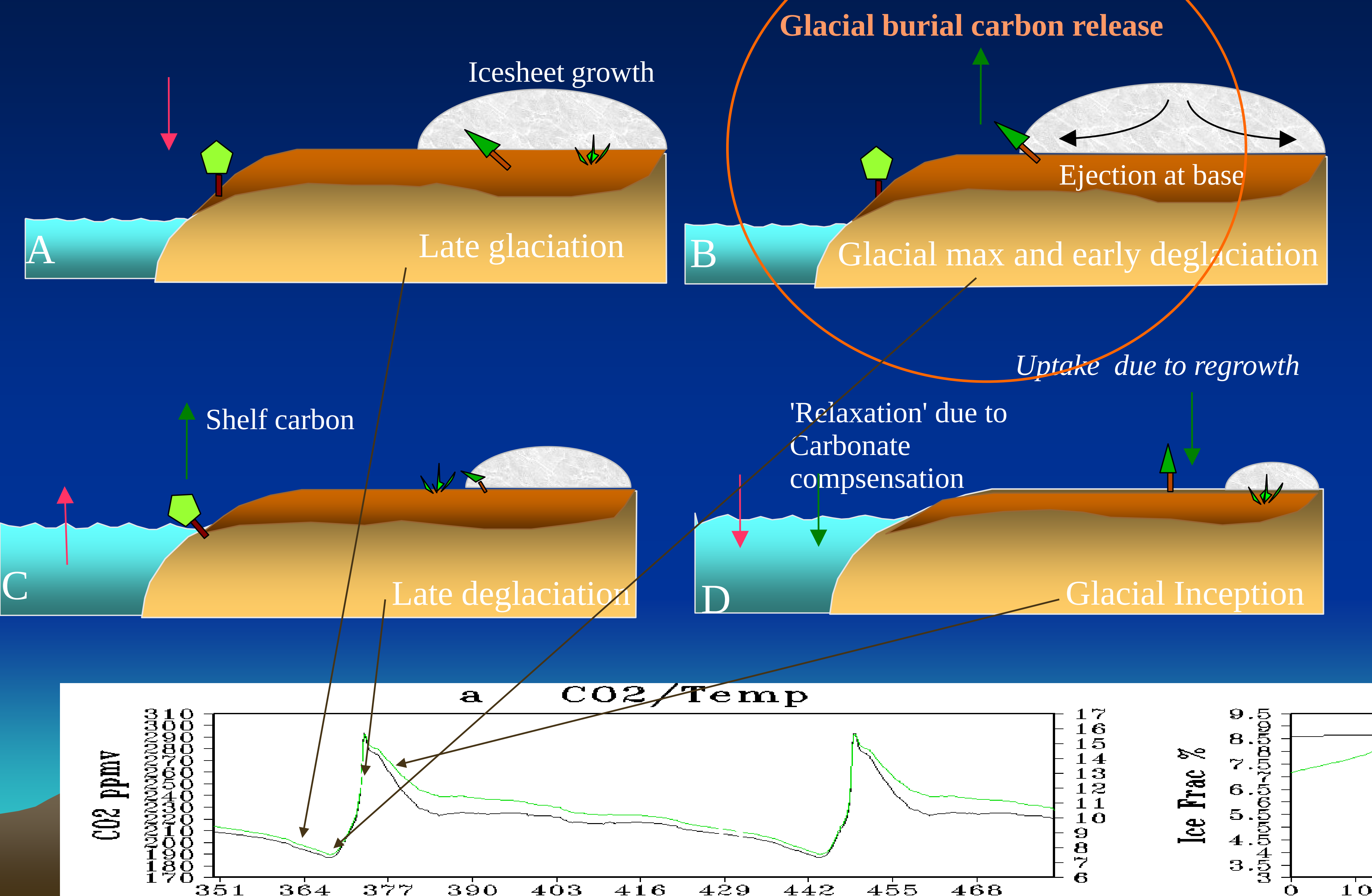
But with large uncertainty: 100-200ppm 0.5-1ºC

Major differences in land response:
Using variability as a testbed; understanding processes and mechanisms for better future projection

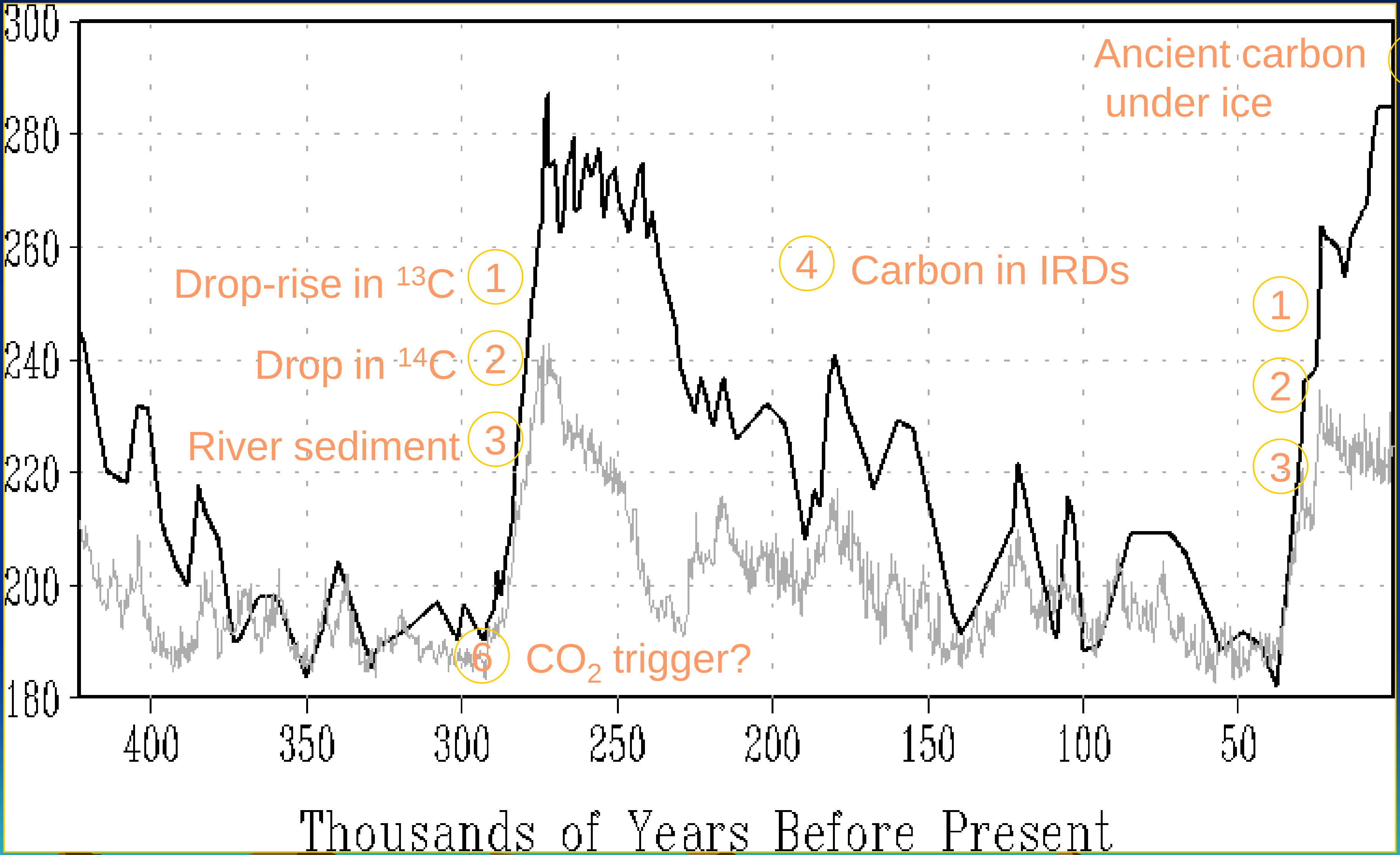
Climate effects: Temperature, precipitation and CO2 fertilization in the future

- Temperature: ~~Lower~~ Higher decomposition rate leads to ~~higher~~ lower storage.
- Precipitation: Slightly ~~drier~~ wetter with regional difference; overall effect small
- CO2 fertilization: High sensitivity; without (or weaker) CO2 fertilization effect, models ~~tend to produce a higher storage at LGM (Kaplan et al. 2002; Otto et al. 2002)~~ will lose carbon (land will switch to a carbon source)

Internally generated quasi-100ky GI cycles due to carbon-climate-icesheet interaction



Summary of Implications/Predictions



Conclusion: CO_2 change

- Contrary to a traditional view, land contributes to deglacial atmospheric CO2 increase. Three main reasons for this difference:

  1 Glacial burial and continental shelf carbon;

  2 Delayed regrowth;

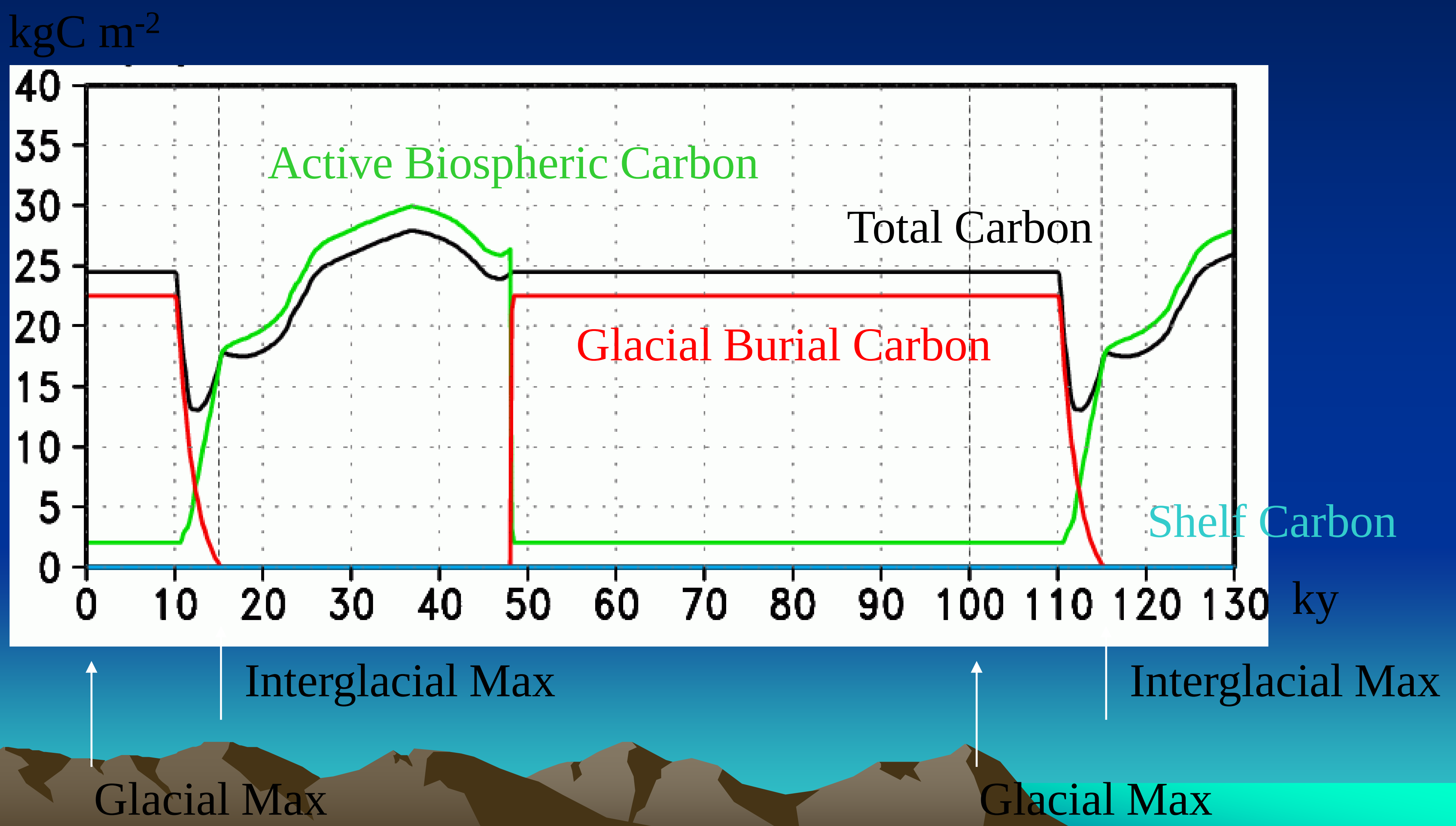
  3 Cold glacial climate increases storage, out-competing lower CO2 fertilization

- Such a sign reversal from -30 ppm to +30 ppm enables the known ocean mechanisms to explain comfortably the rest of the 80-100 ppm change

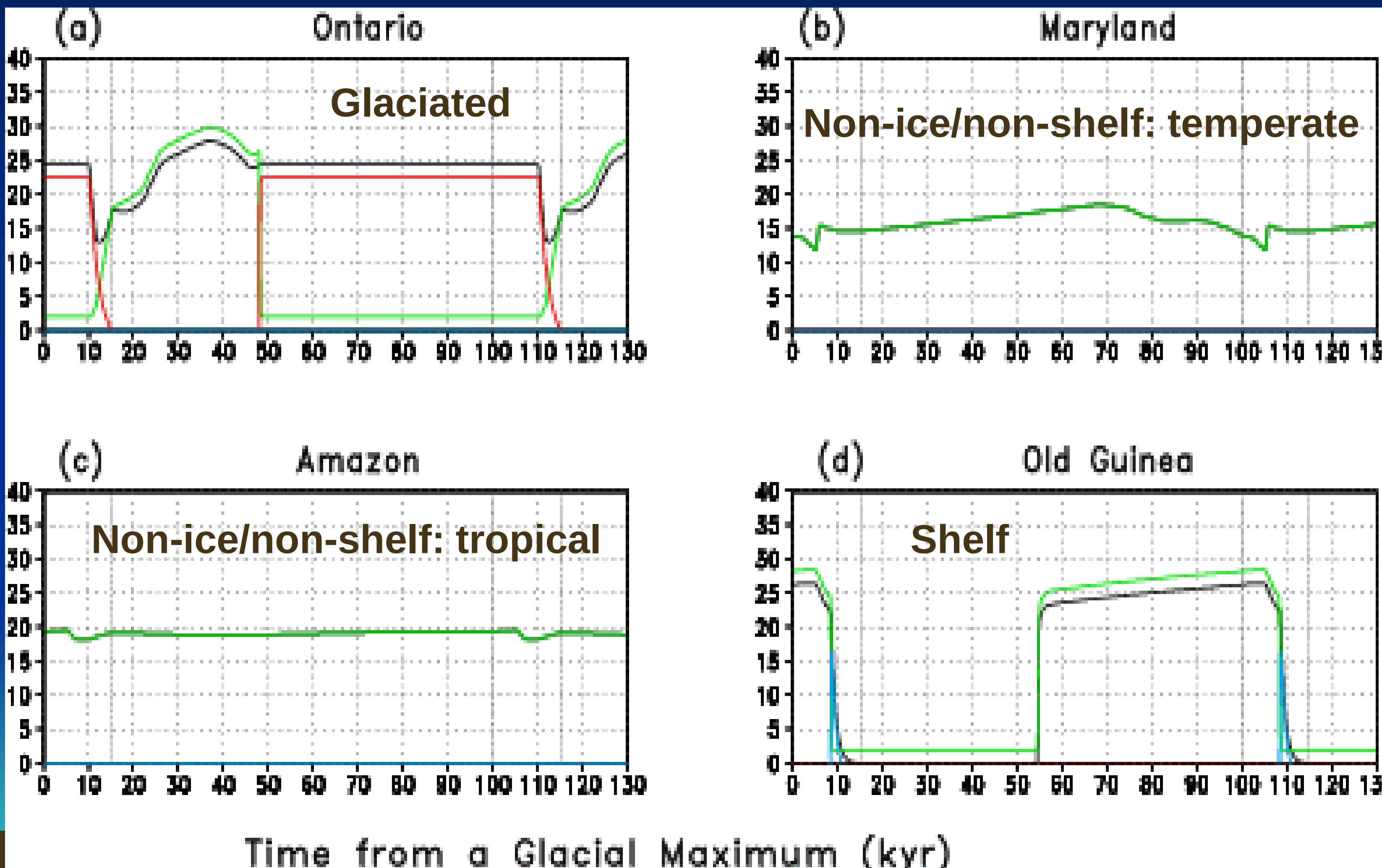
Conclusion: Triggering Mechanism

- Carbon-climate-icesheet interaction can (but not necessarily) lead to self-sustaining glacial-interglaical cycles. Key triggering mechanisms:
  - Glacial inception: CO_2 'rebound' as burial CO_2 is slowly absorbed into ocean/sediment, and regrowth uptake
  - Deglaciation: glacial burial carbon is ejected out of a main icesheet when grows long and large enough, triggering increase in CO_2 and temperature, leading to a series of feedbacks.
- Interaction with orbital forcing to produce the complexity of observed G-I cycles
- We should not be disappointed by such complexity, but rather be open-minded

130ky change in carbon pools : Ontario (glaciated)



130ky simulation for various places

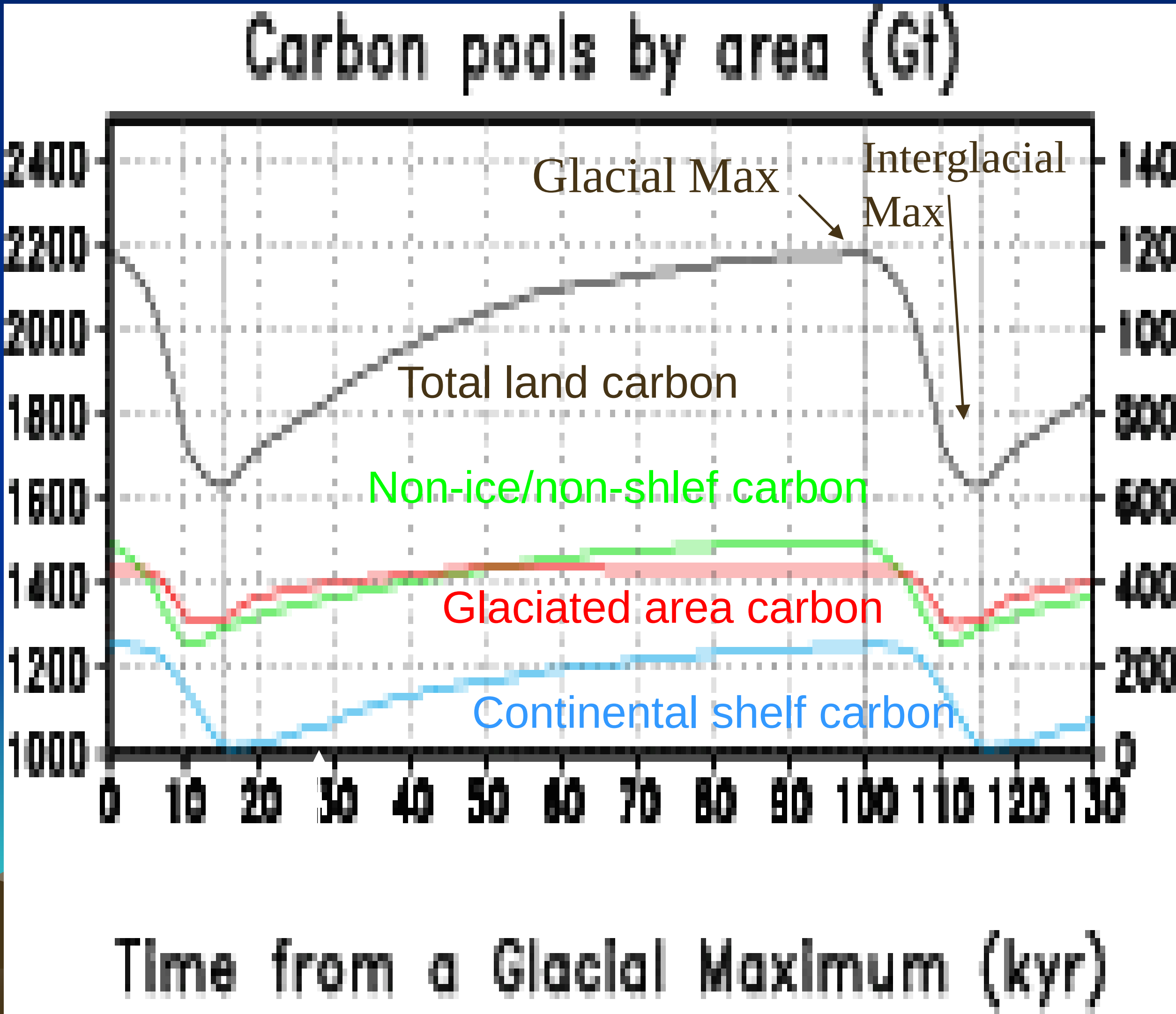


Land carbon change by type

During deglaciation, land loses, not gains, carbon by 500-600 GtC, with contribution from:

1. Glaciated area (Canada, Scandinavia, etc.): 100GtC
2. Continental shelf area: 200GtC
3. The rest, non-ice/nonshelf area: 200GtC

But they are transient!



The ‘perpetual’ mystery of the glacial-interglacial cycles --- a way out ?

- The Milankovitch orbital theory has enjoyed great success as the pacemaker in explaining the glacial-interglacial cycles

- However, major puzzles remain; for instance
  - The glacial CO2 problem
  - The role of carbon-climate interaction
  - Timing of events (‘causality problem’)

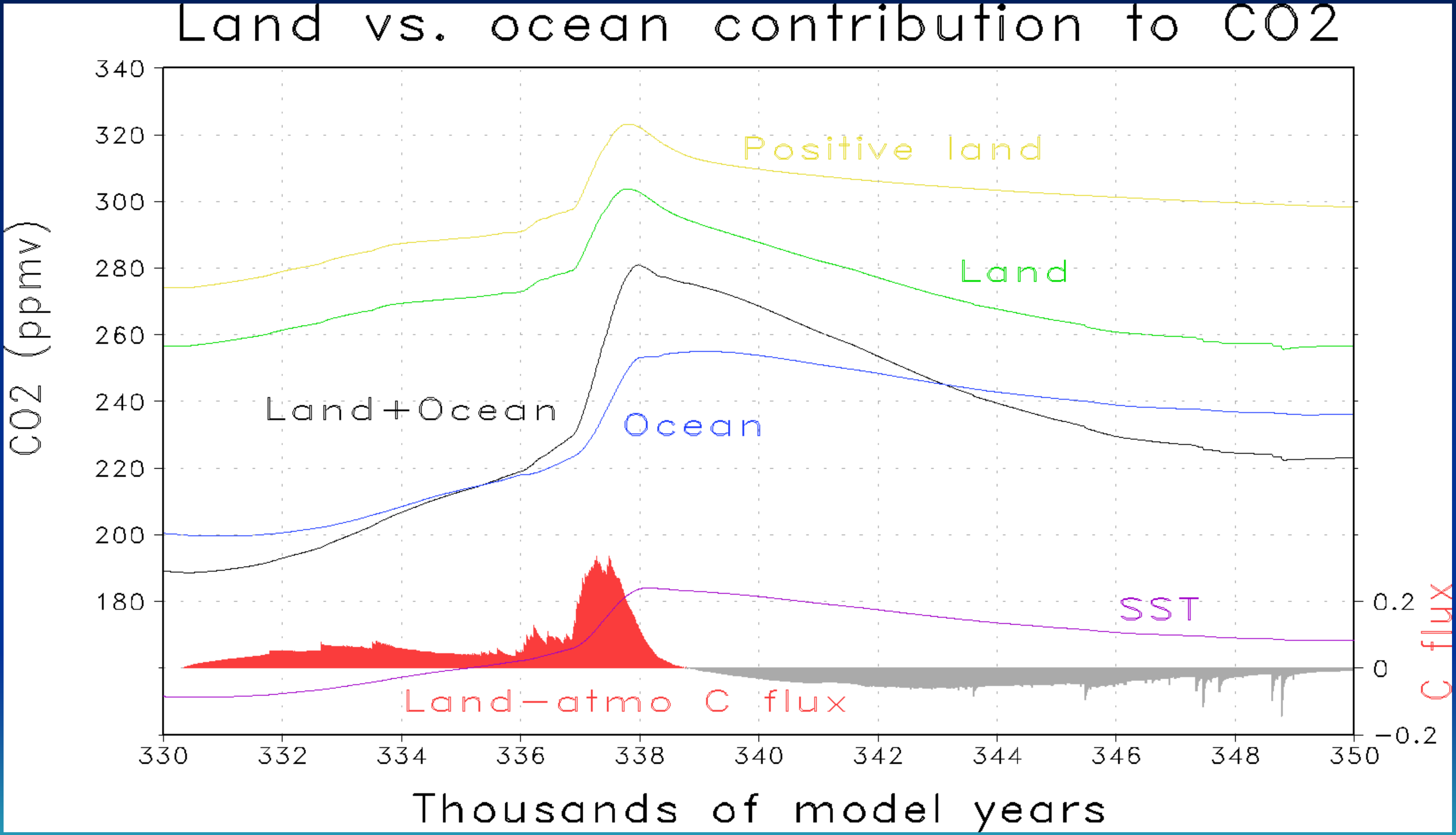
- New attempts: Paillard and Parrenin (2004), Toggweiler et. al (2006), both involving southern ocean carbon-climate interaction as trigger;

  and **this proposal**:

  a carbon-climate-icesheet interaction theory involving the burial and release of organic carbon under the icesheets that may be the missing link

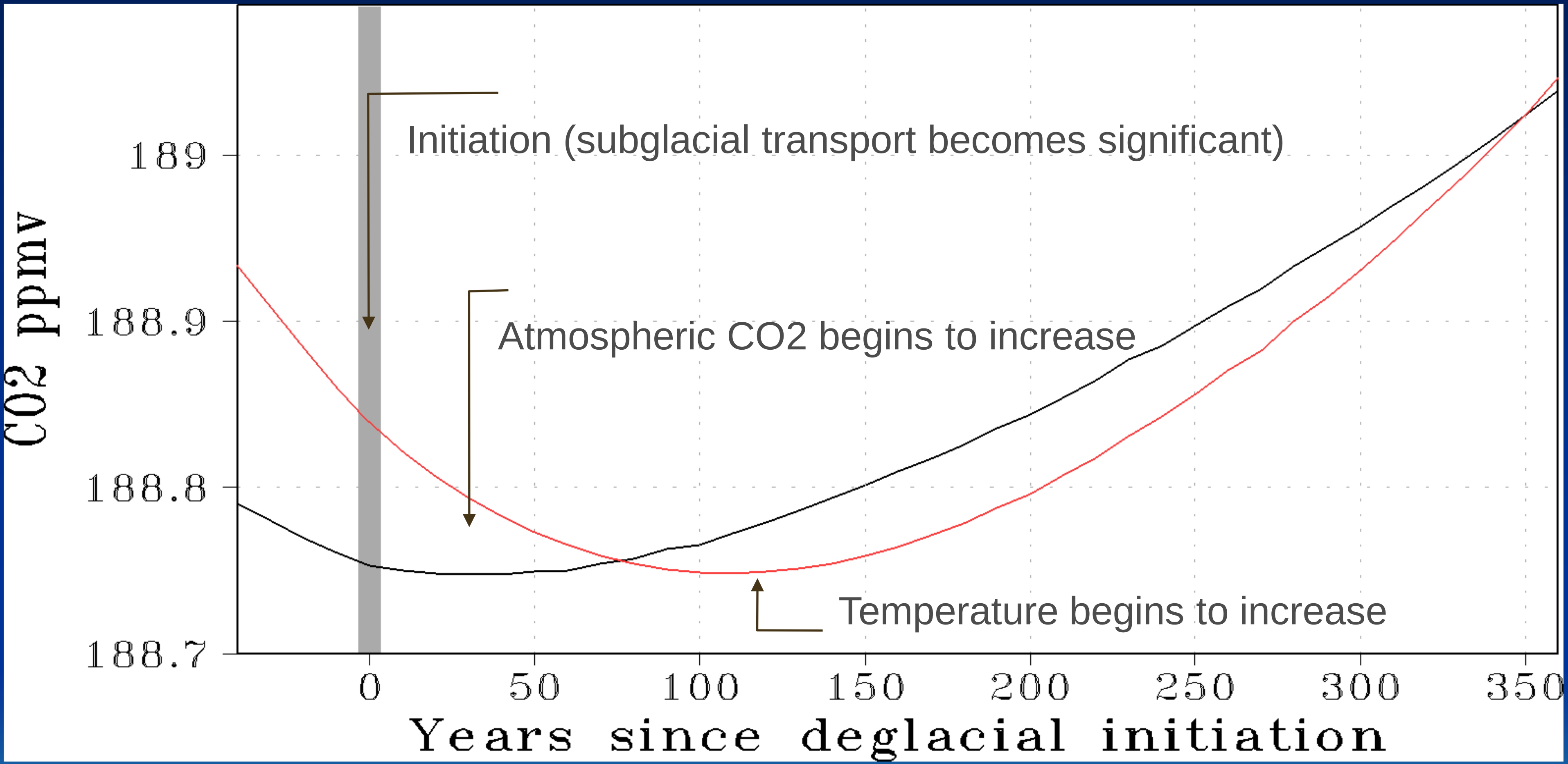
Details described in Zeng (2003), Zeng (2007)

Deglaciation and Glacial Inception



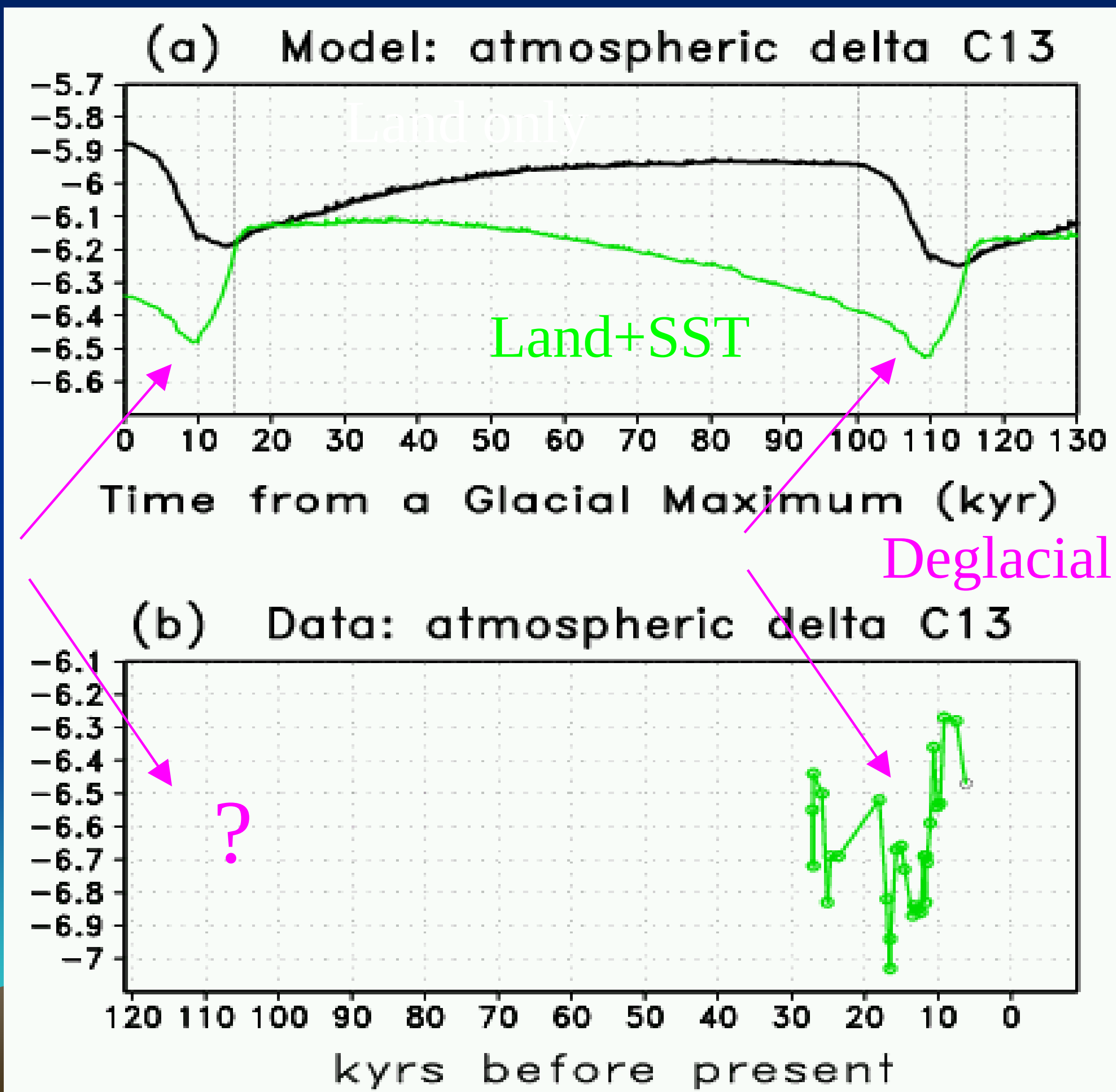
20 thousand years

Timing of events at a termination



(If CO2 triggers termination)
Temperature lags CO2 by 50-100 years
→ near synchronous in paleo record?

Prediction I: dC13 drops initially at deglaciation due to land carbon release followed by a rise in response to oceanic warming and regrowth on land



Modeled atmospheric C13

Air trapped in ice core at Taylor Dome, Antarctica

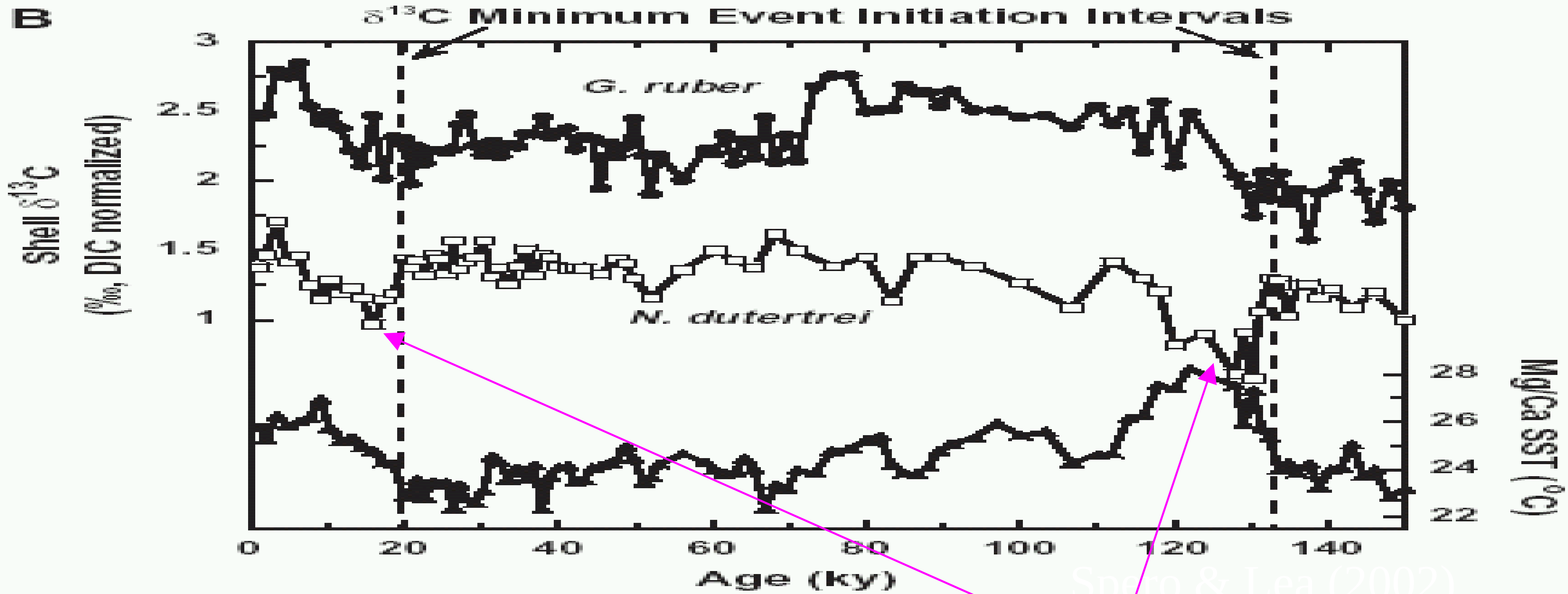
Smith et al. (1999)

Prediction II: Ocean C13 and Atmospheric C14

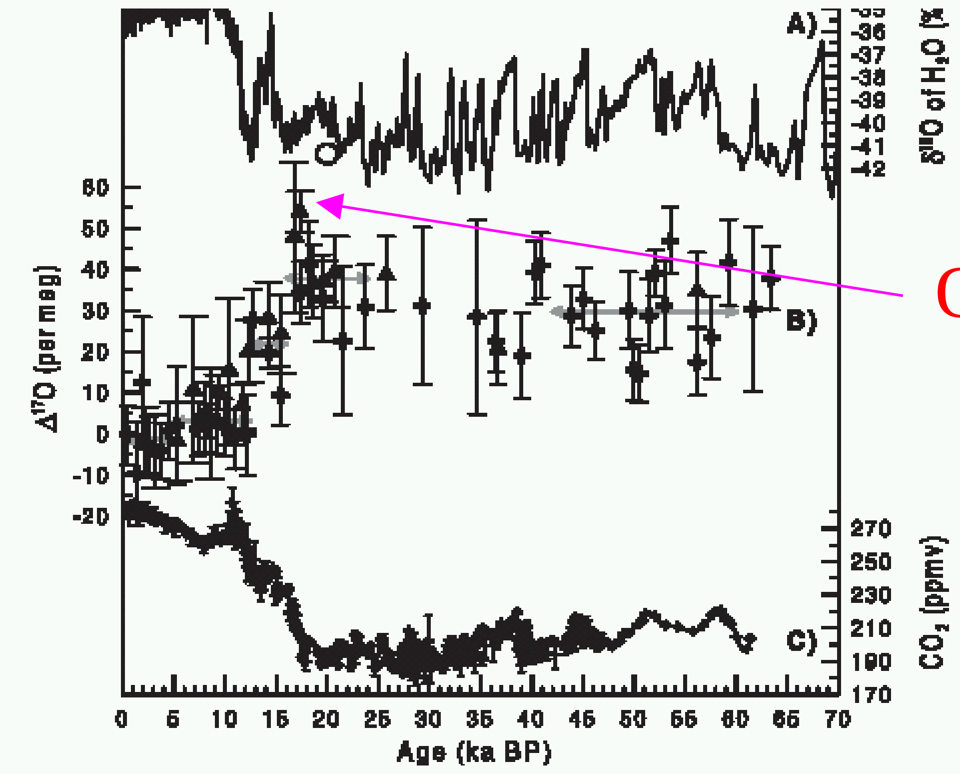
- Surface ocean $\delta^{13}C$ would also show a drop-rise transition at deglaciation because of the fast exchange with the atmosphere, except where the influence of thermohaline circulation change is large

- Deep ocean $\delta^{13}C$? (contradicts traditional marine C13 interpretation)
  - Alternative explanations: (1) Carbonate ion effect (Spero et al., 1997); (2) Increased stratification (Toggweiler et al., 2006)

- Input of ^{14}C-dead organic carbon from Eemian may drive down atmospheric $\Delta^{14}C$ by 100-200‰ at the deglaciation after LGM



Spero & Lea (2002)

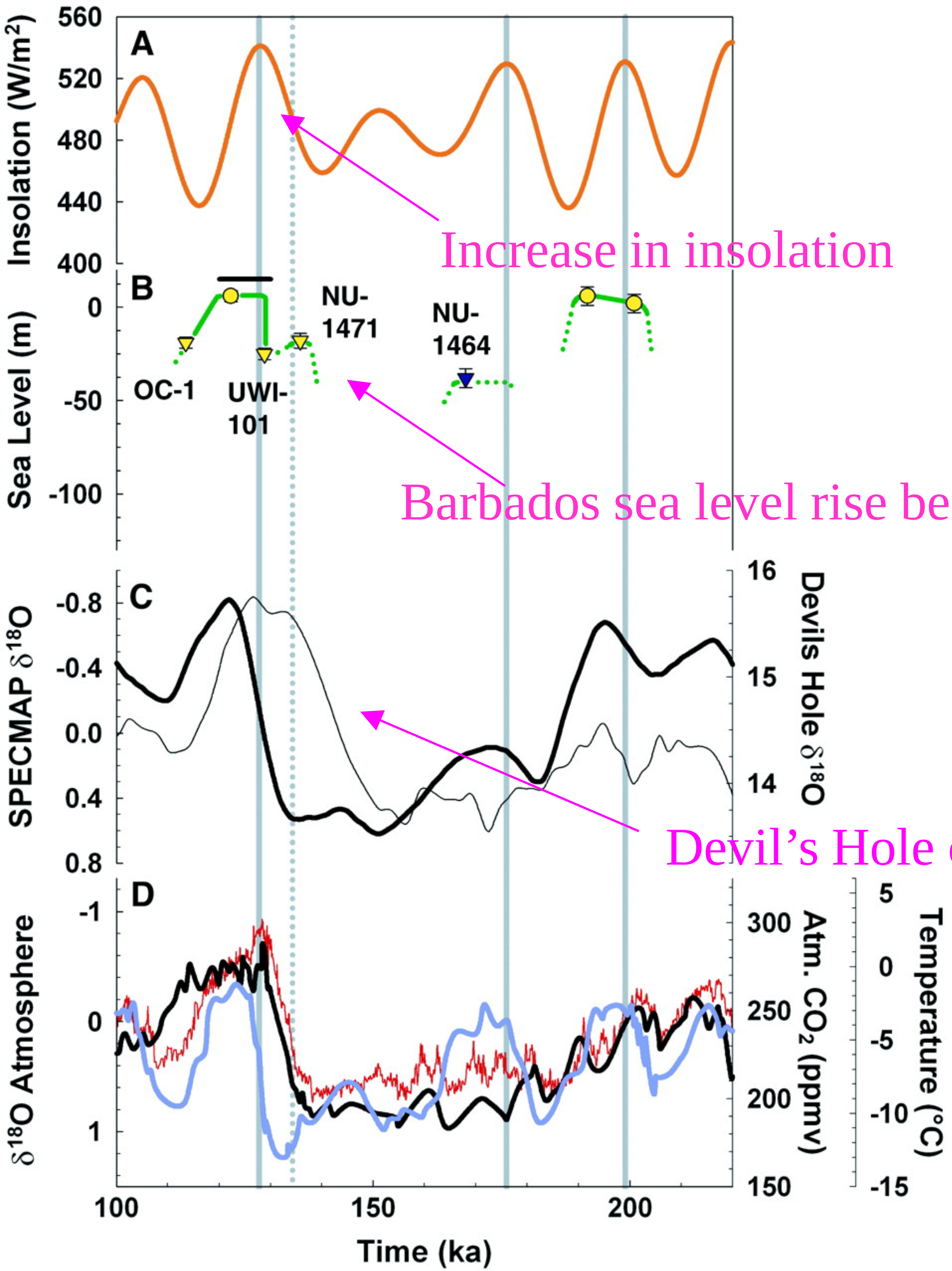


Deglacial C13 minima
(Spero and Lea, 2002)

Oxygen 17 max:
another indicator of deglacial
land carbon release?

Blunier et al. (2002)

Termination II: a candidate for CO_2 triggering?



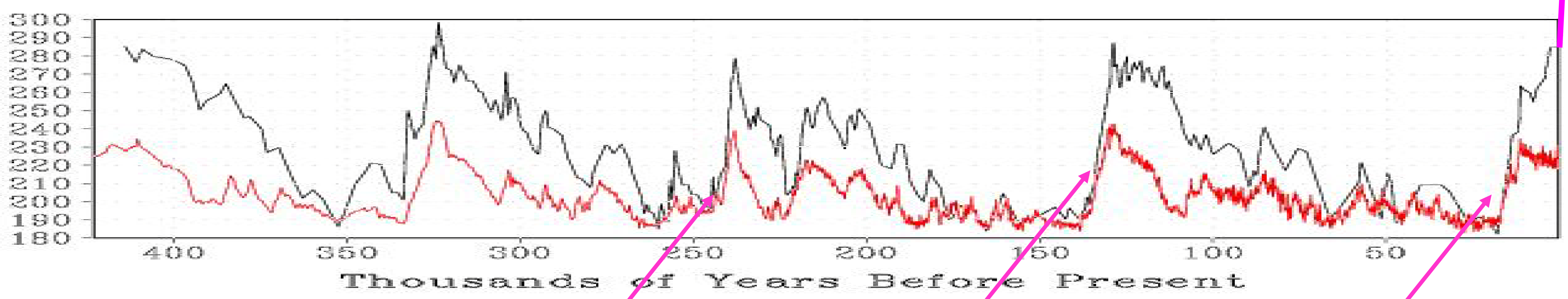
Increase in insolation

Barbados sea level rise before insolation (Gallup et al. 2002)

Devil’s Hole calcite (Winograd et al., 1992)

Which terminations might have been triggered by CO2?

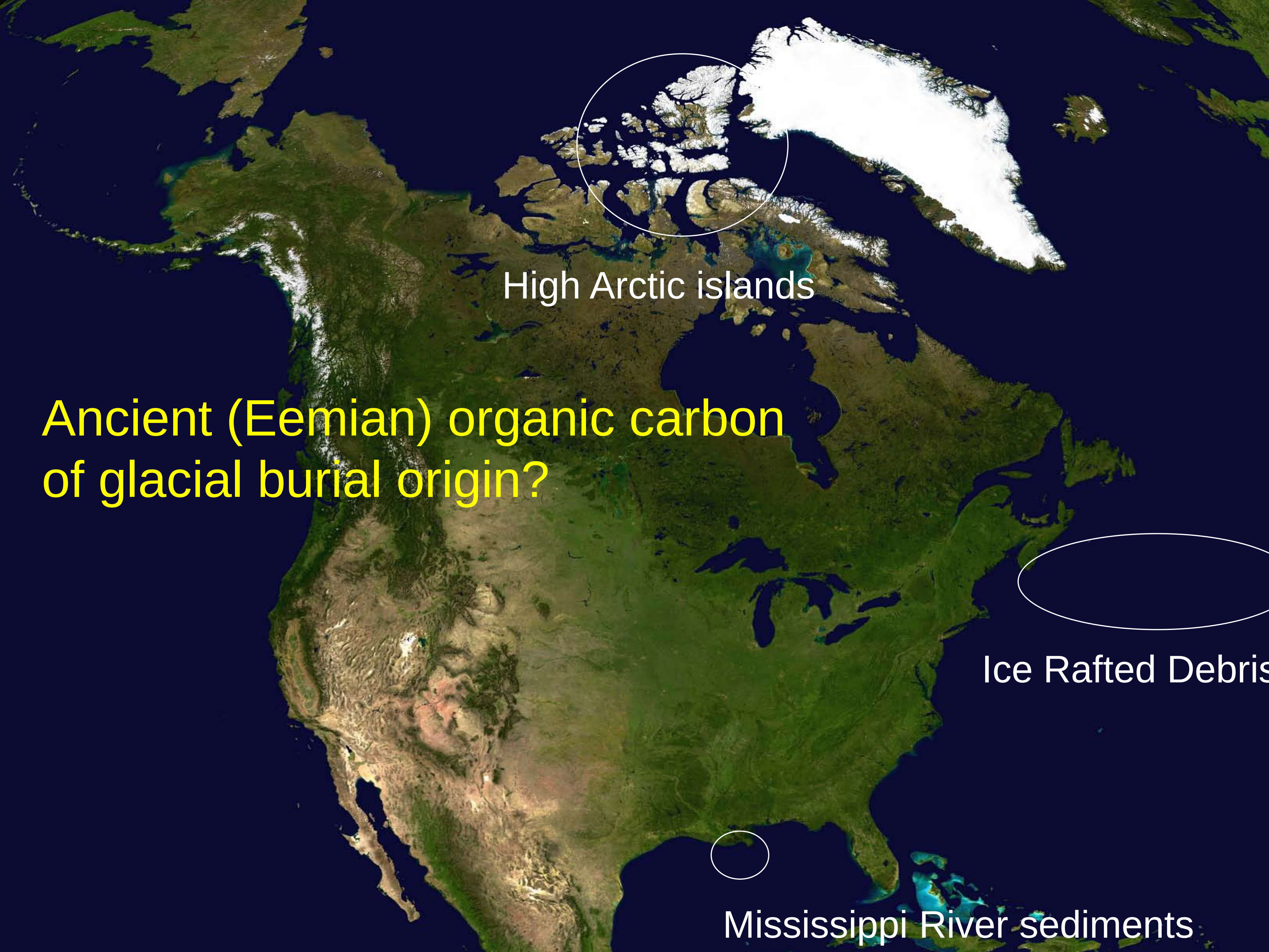
- The terminations triggered by glacial burial CO2 ejection are likely those preceded by long-lasting and cold glaciation during which icesheets can grow to large size: Termination II is a good candidate



Probably not

Good probability

Maybe,
Maybe not?


High Arctic islands
Ancient (Eemian) organic carbon
of glacial burial origin?
Ice Rafted Debris
Mississippi River sediments

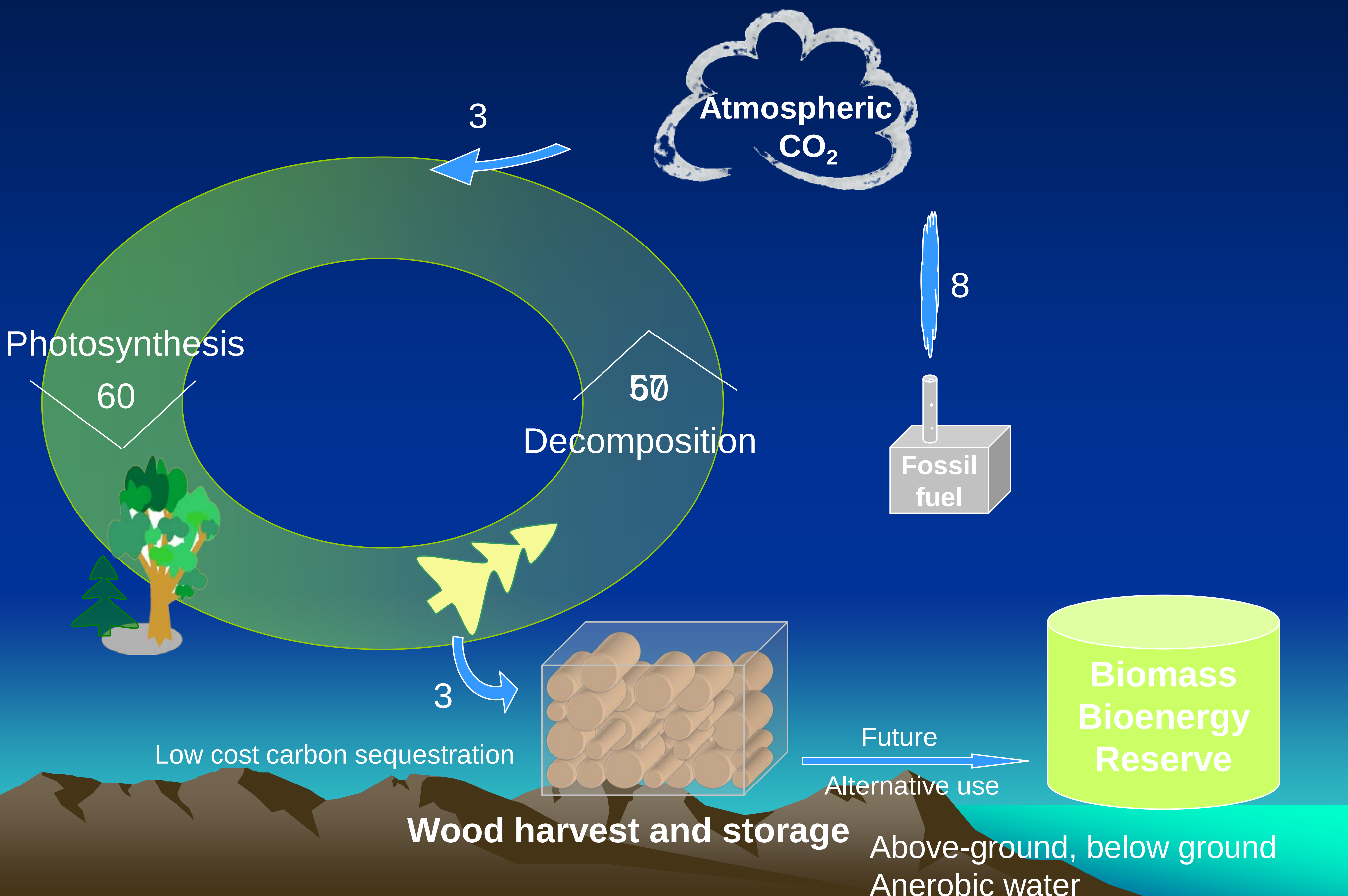

Ancient organic carbon of glacial burial origin?
King George Island, Antarctica

Thank You

Paleoclimate study gives us insight about future climate change.
Can it also inform us about climate change mitigation/adaptation?

If interested, I have one more slide…

Carbon sequestration via wood harvest and storage



Role of Land

Typical partitioning of deglacial CO2 change (Holocene – LGM):

- Atmosphere +180 Gt (90 ppm increase)
- Land +500 Gt (increase)
- Ocean - 680 Gt (decrease)

Land is an additional 30ppm burden that ocean carbon pool has to accommodate, i.e., ocean needs to explain 120ppm increase in atmospheric CO2

Why glacial land carbon pool is smaller?

The colder/drier glacial climate and lower CO2 are less favorable for vegetation growth, so less carbon stored on land

Consequences to deglacial CO_2

A release of 500 Gt land carbon would lead to an atmospheric CO_2 increase by:

1. 240 ppmv if release is instantaneous
2. 120 ppmv in 10 years (upper ocean)
3. 45 ppmv in 1000 years (deep ocean uptake)
4. 15 ppmv in 10000 years (sediment dissolution)