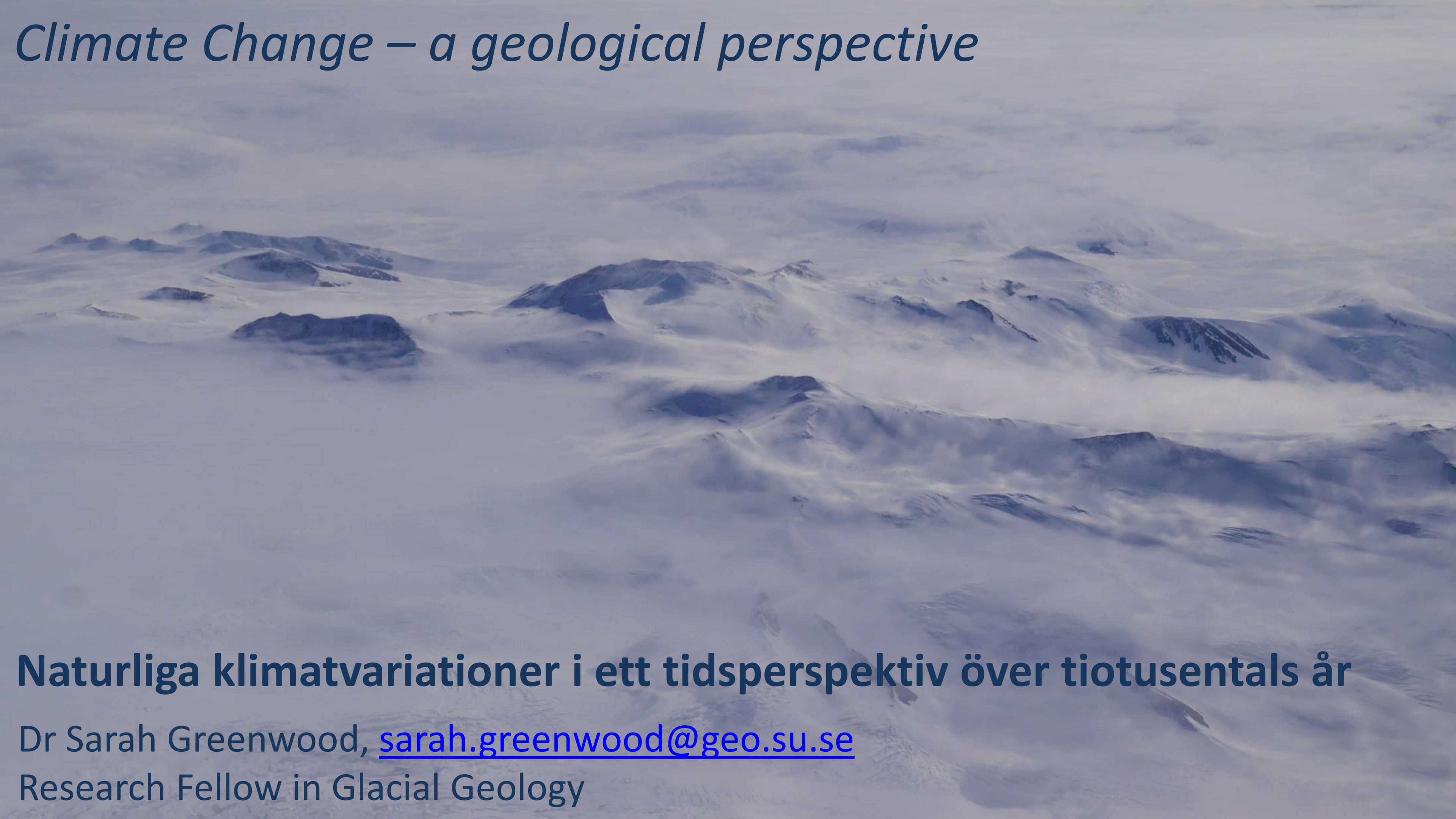
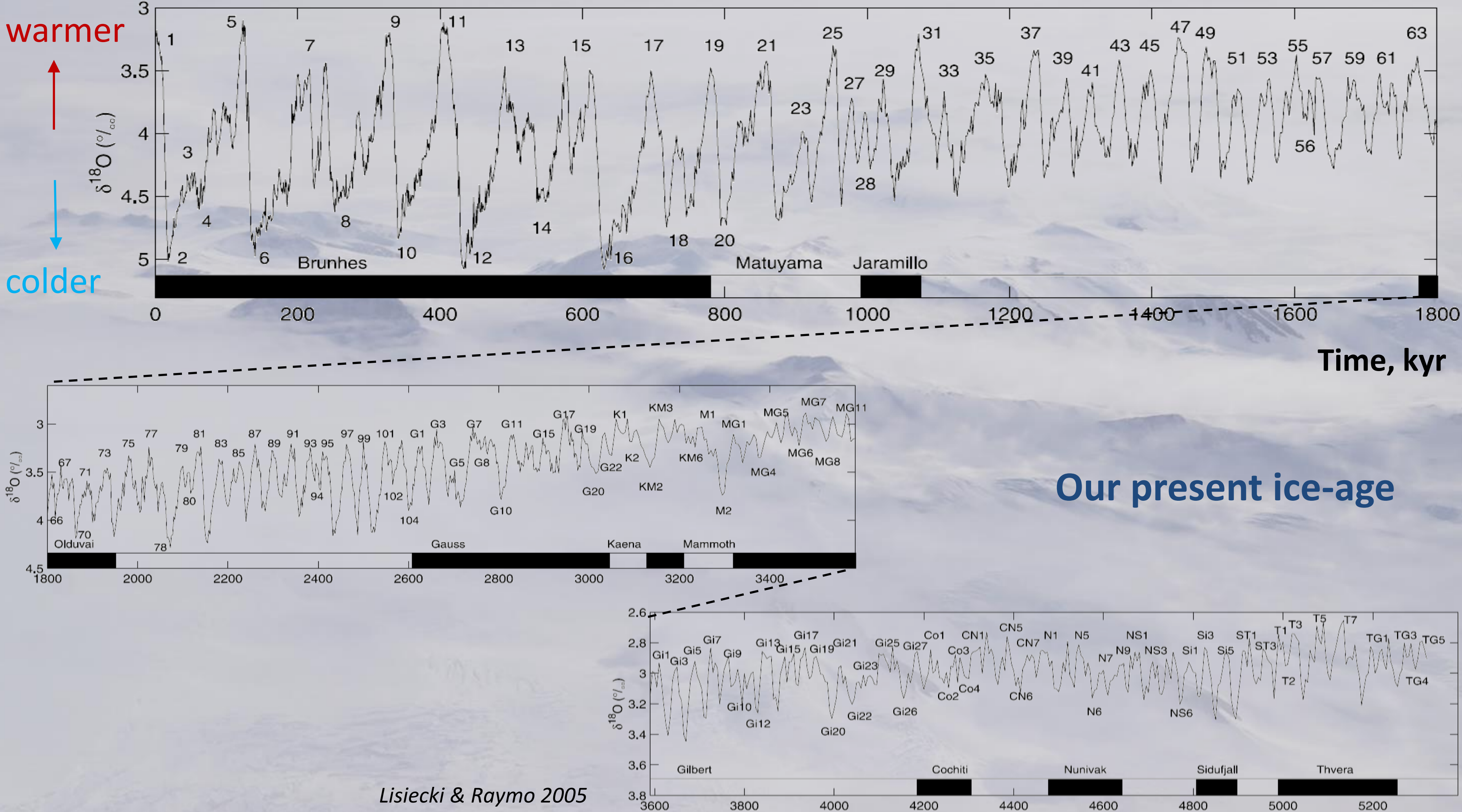
Climate Change – a geological perspective



Naturliga klimatvariationer i ett tidsperspektiv över tiotusentals år

Dr Sarah Greenwood, sarah.greenwood@geo.su.se
Research Fellow in Glacial Geology



Our present ice-age

Lisiecki & Raymo 2005

Today’s lectures

The Last Glacial Maximum – ice sheets, sea level, climate

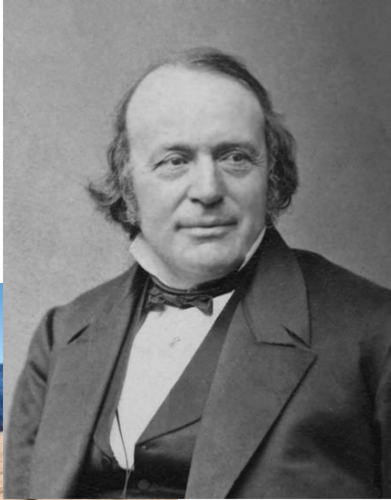
The Plio-Pleistocene (present) ice age – repeated (cyclical) and widespread glaciation of the northern hemisphere

Controls on ice sheet growth and decay – Milanković orbital theory

The ice–ocean–climate system responses

The Last Glacial Maximum

Louis Agassiz, 1840.
Études sur les glaciers.



Discovery of past continental ice sheets ('glacial theory'): terrestrial glacial geology (1830s)

Unsorted 'drift': till
(morän)

Striations
(isräfflor)

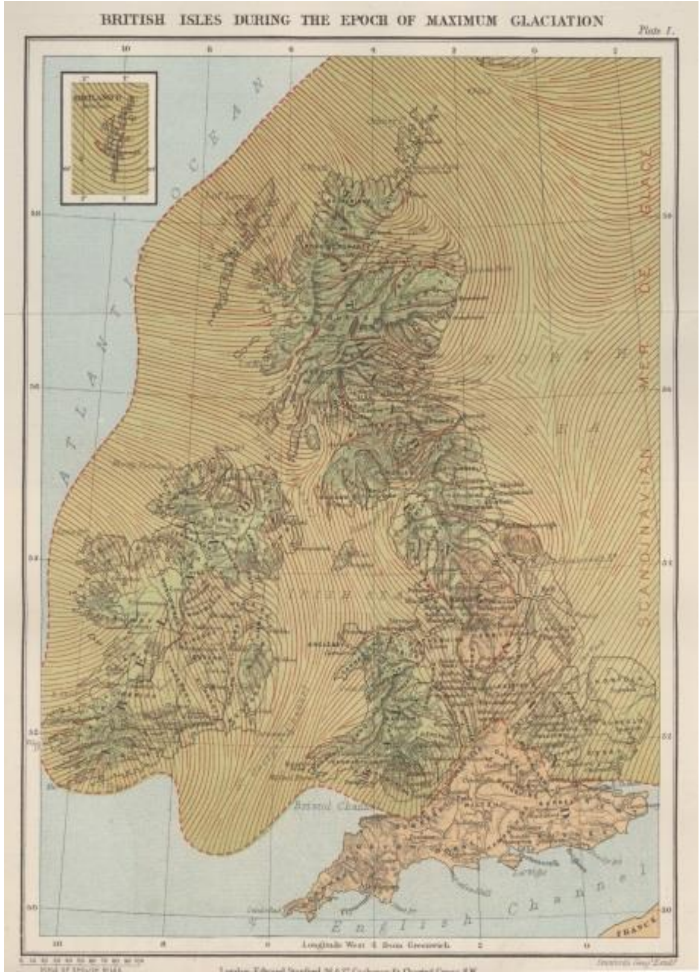
Erratic boulders
(flyttblock)

Pictures from nsidc.org, S.G., public domain

The Last Glacial Maximum

Discovery of past continental ice sheets (‘glacial theory’): terrestrial glacial geology (1830s)

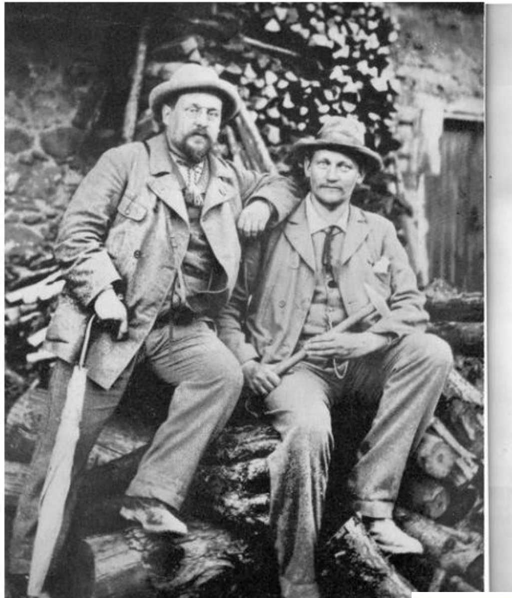
Based on Chamberlin 1894

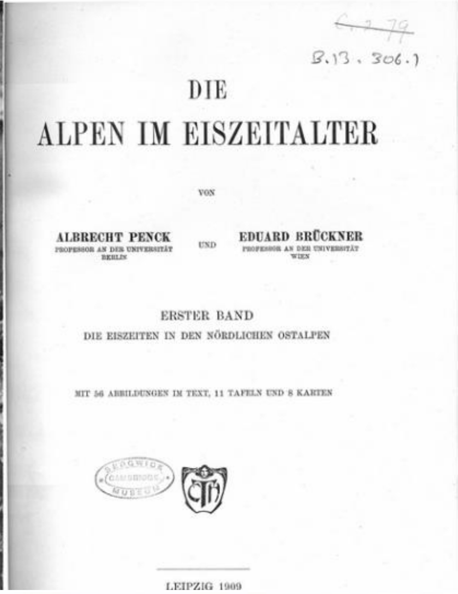


Geikie 1894

The Last Glacial Maximum

Discovery of past continental ice sheets (‘glacial theory’)





DIE
ALPEN IM EISZEITALTER

VON

ALBRECHT PENCK
PROFESSOR AN DER UNIVERSITÄT
BERLIN

UND

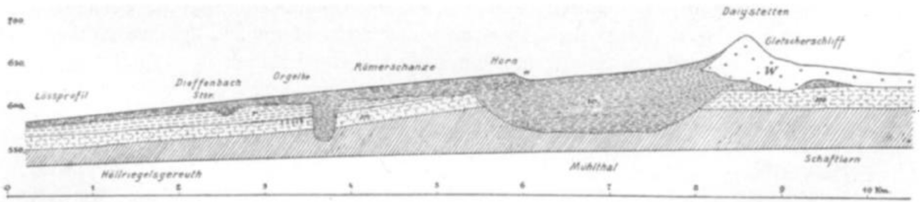
EDUARD BRÜCKNER
PROFESSOR AN DER UNIVERSITÄT
WIEN

ERSTER BAND
DIE EISZEITEN IN DEN NÖRDLICHEN OSTALPEN

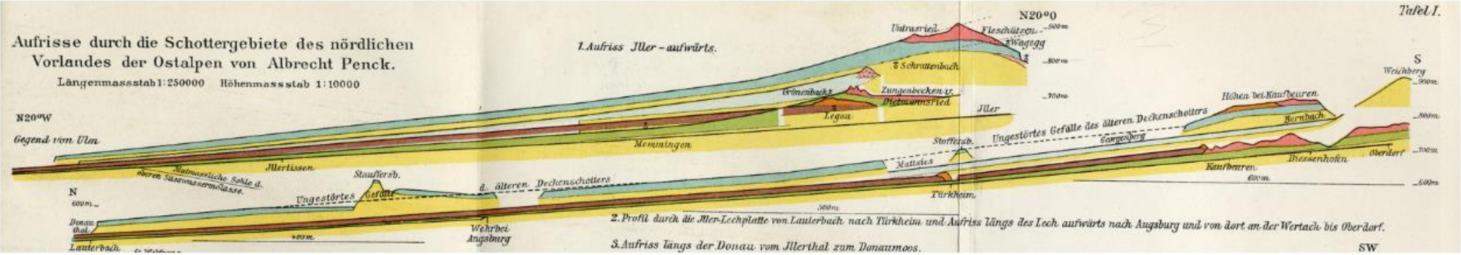
MIT 56 ABBILDUNGEN IM TEXT, 11 TAFELN UND 8 KARTEN

LEIPZIG 1909

Four continental glaciations (Penck & Brückner 1909)
(Würm, Riss, Mindel, Günz)

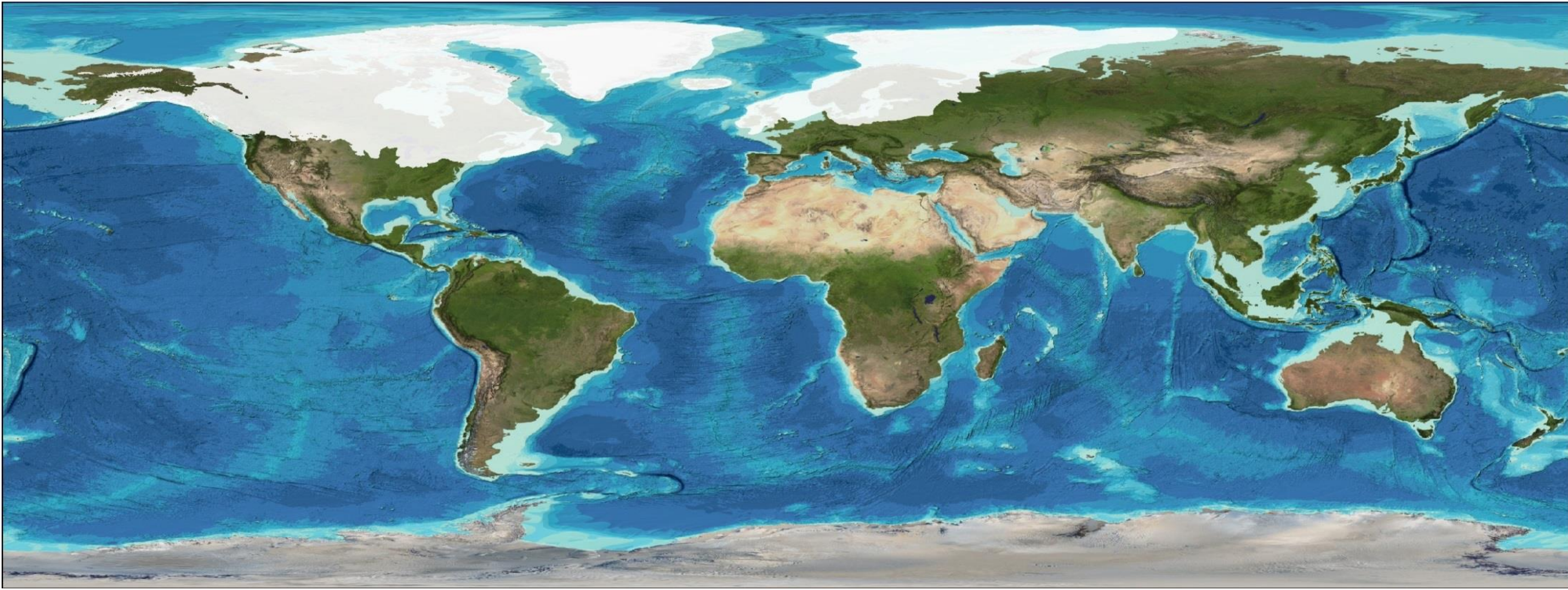


W = Würmmoräne, *w* = Niederterrassenschotter, *r* = Hochterrassenschotter, *m* = jüngerer Deckenschotter, schraffiert = Flinz.



Images from Subcommission on Quaternary Stratigraphy

The Last Glacial Maximum – ice sheets



The Last Glacial Maximum – ice sheets

Photos: S.G.

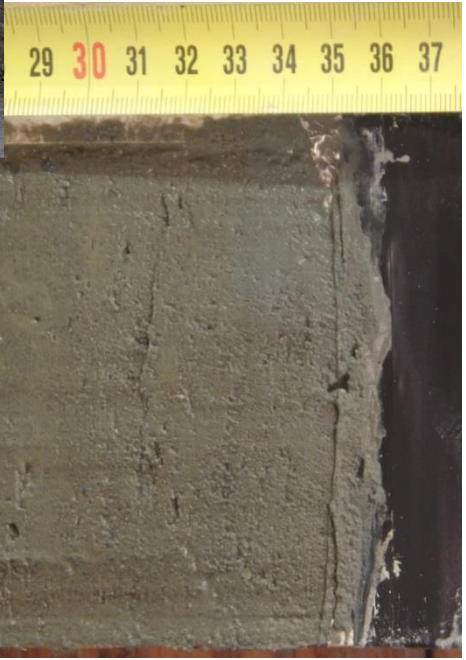
Terrestrial glacial deposits

Sediments deposited into dammed lakes (forming deltas)

Deformed, crushed and unsorted sediments ('diamicts')

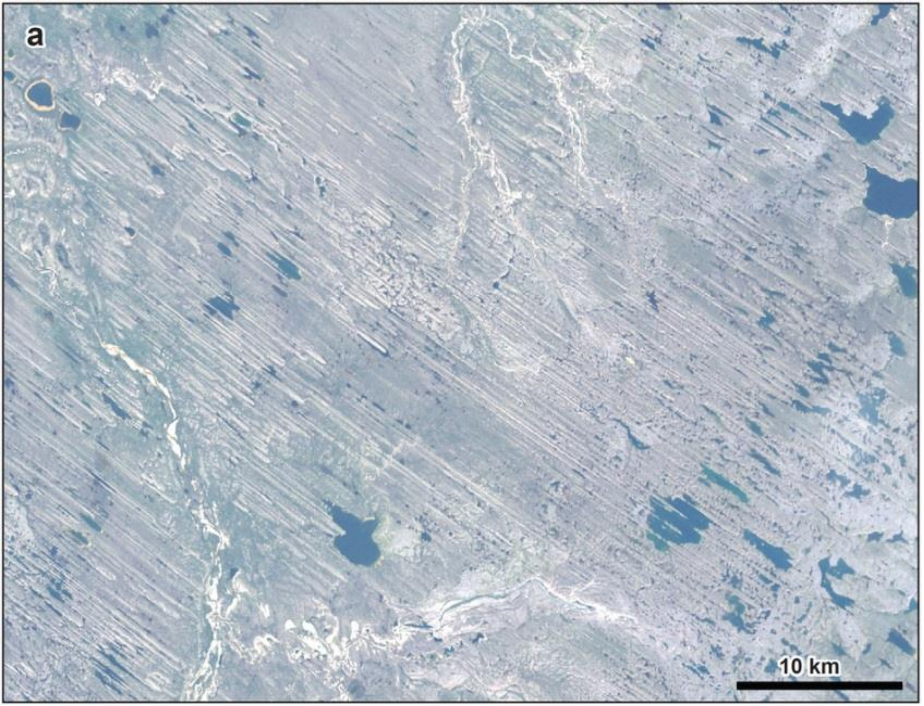
Marine glacial deposits

Sediment clasts in a mud matrix



The Last Glacial Maximum – ice sheets

Terrestrial glacial landforms



Stokes et al 2016

Linear, streamlined hills
(drumlins, crag-and-tails,
roches moutonnées/rundhällar)

The Last Glacial Maximum – ice sheets

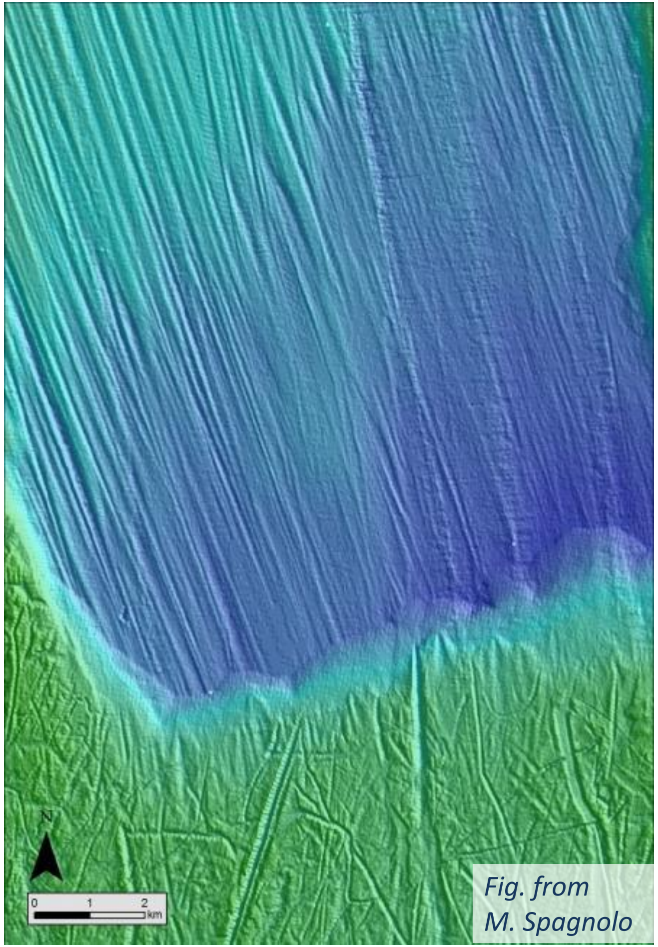
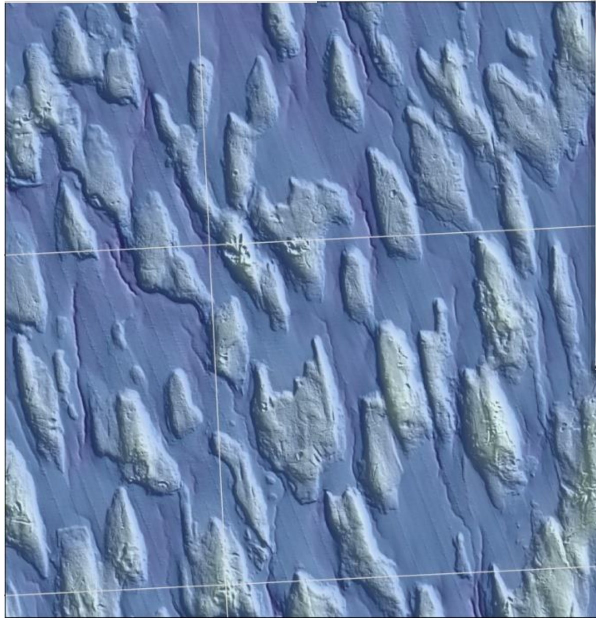


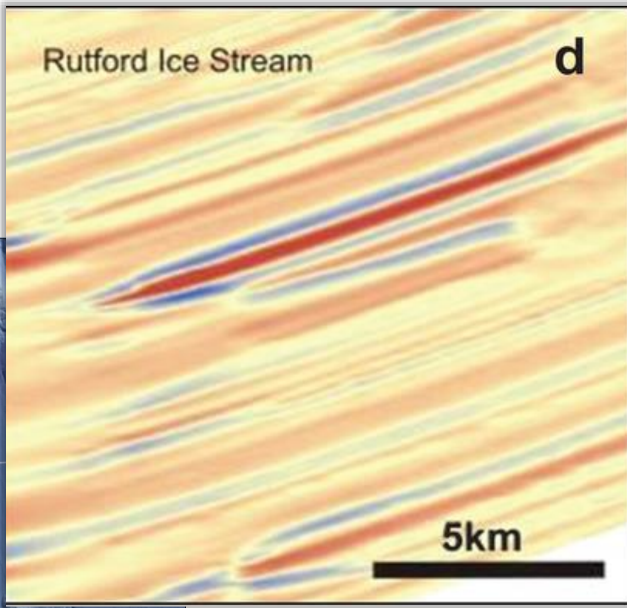
Fig. from M. Spagnolo

Marine glacial landforms

Greenwood et al 2017

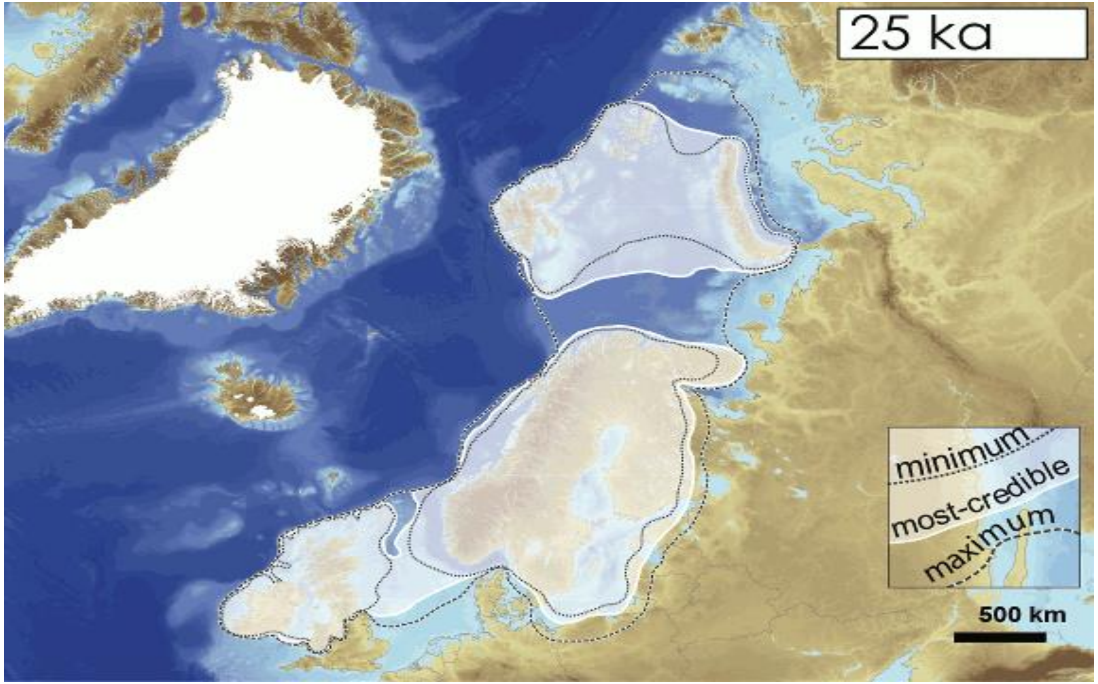


Contemporary ice sheet landforms



King et al 2009

The Last Glacial Maximum – ice sheets



Hughes et al. 2016

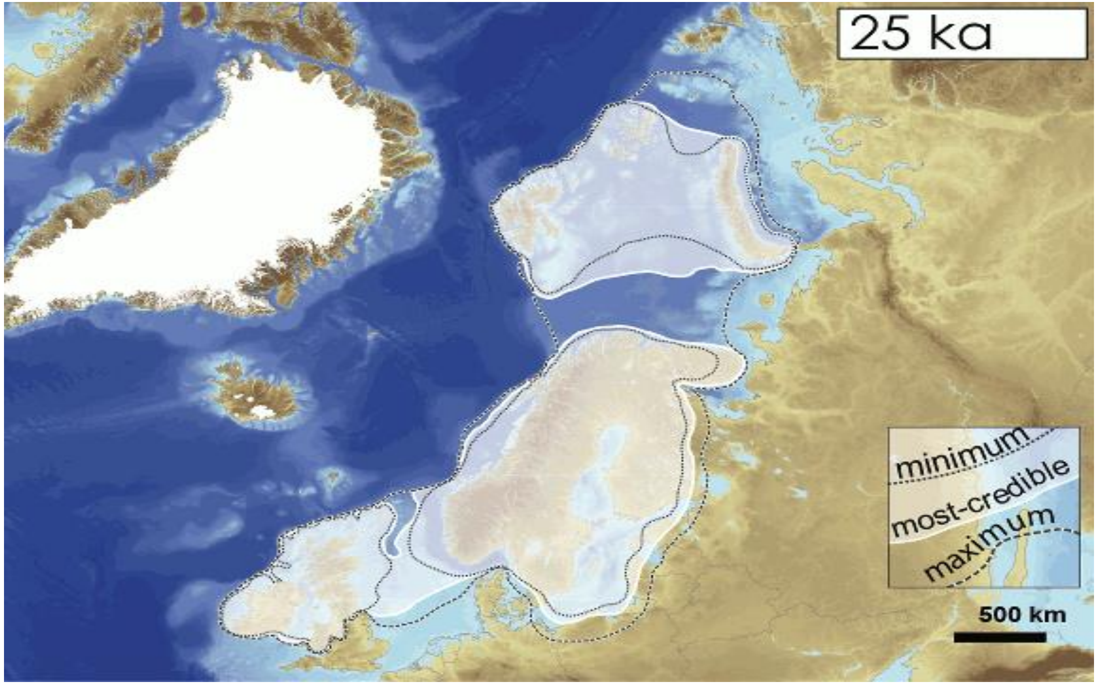
Reconstruction based on dated geological deposits

Growth out of (and demise to) mountain sources

When ice is thick enough, it will grow beyond land onto the seafloor

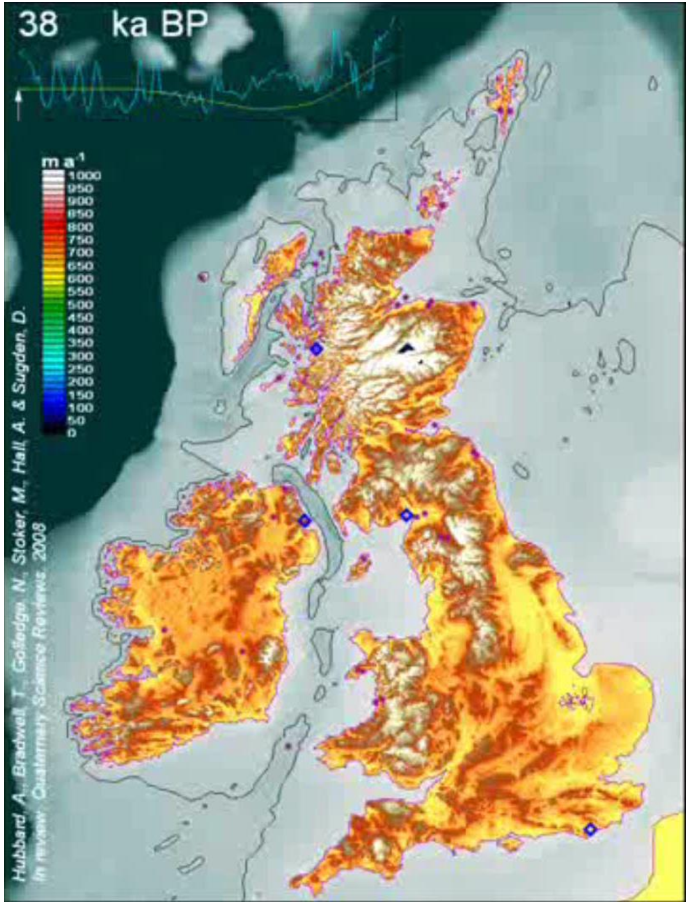
Growth to the NW limited by the edge of the continental shelf

The Last Glacial Maximum – ice sheets



Hughes et al. 2016

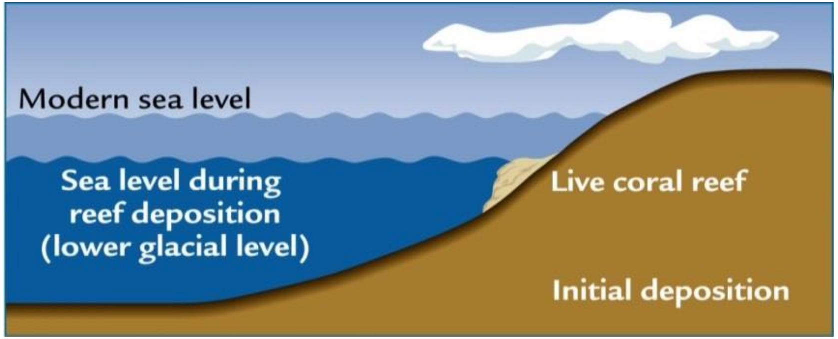
Hubbard et al. 2009



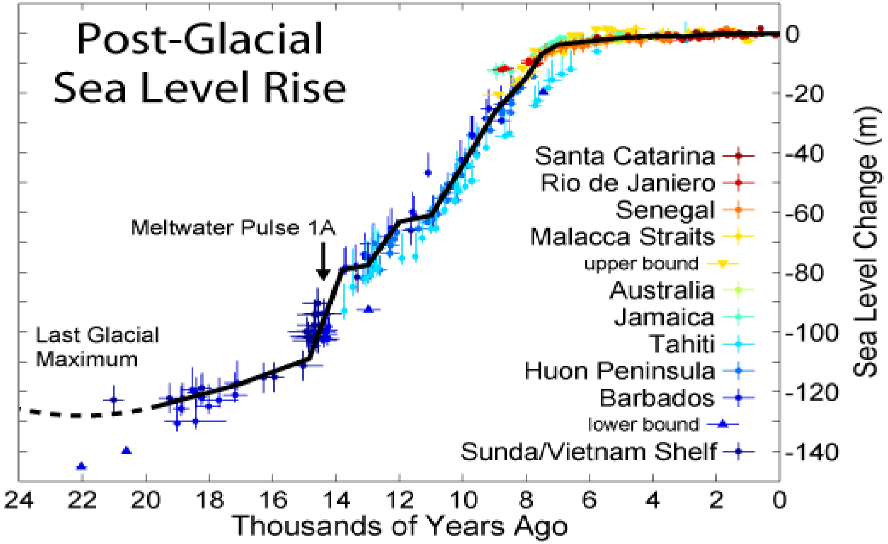
Reconstruction based
on ice flow physics

The Last Glacial Maximum – sea level

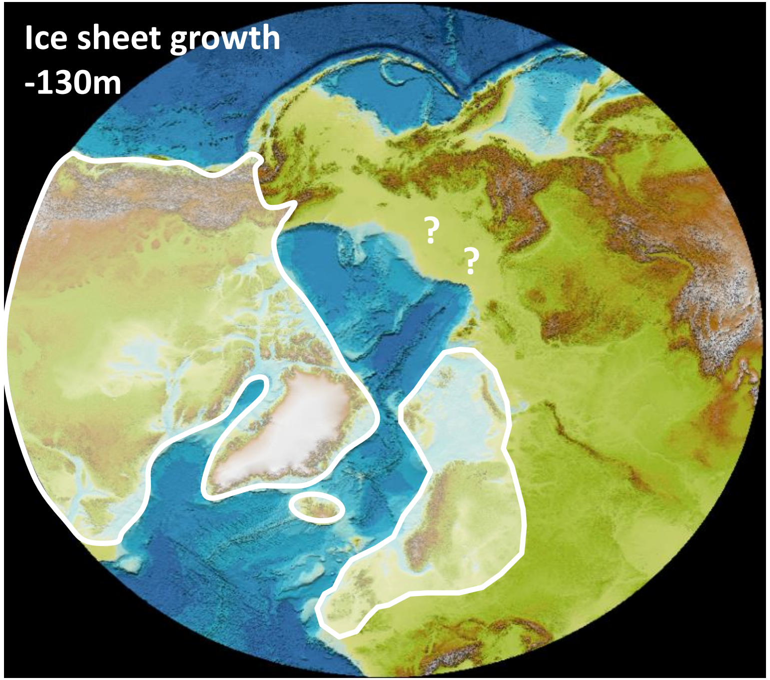
Ruddiman 2014



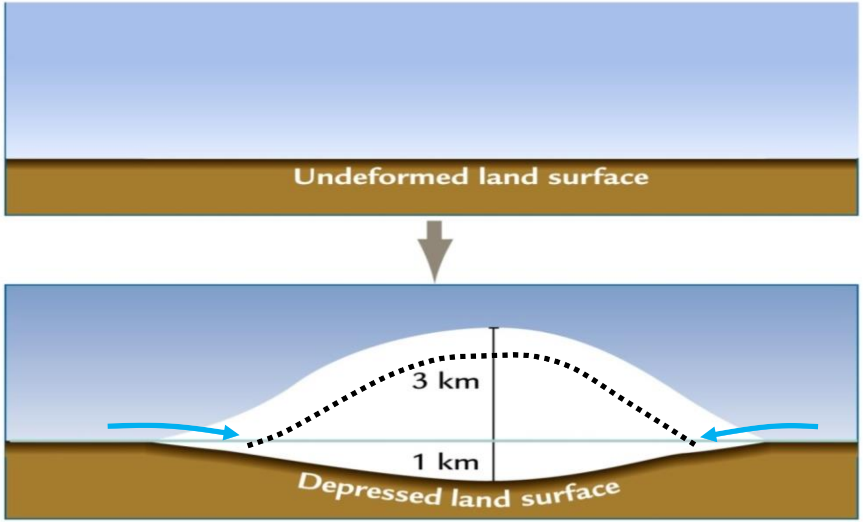
Corals = sea level markers



antarcticglaciers.org



The Last Glacial Maximum – sea level

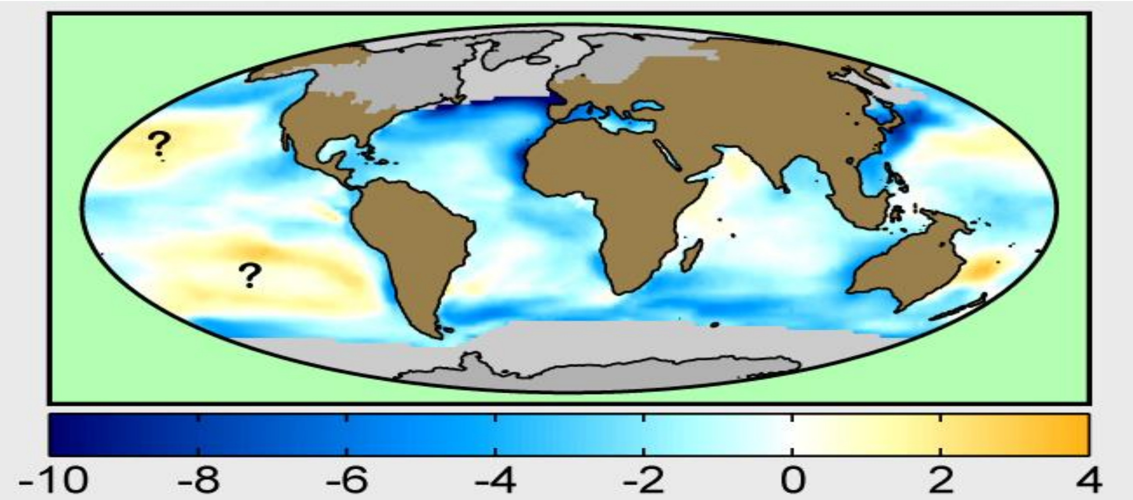


Modified from Ruddiman 2014

Local or '***relative*** sea level' history due to combined effects of:

- global increase in ocean volume
- isostatic rebound

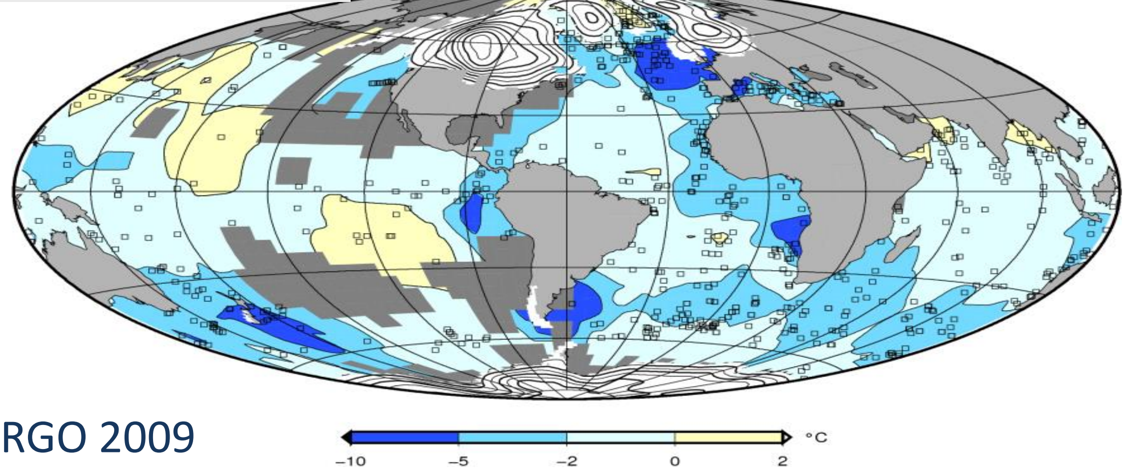
The Last Glacial Maximum – temperature



Sea surface temperature, relative to today

CLIMAP 1981

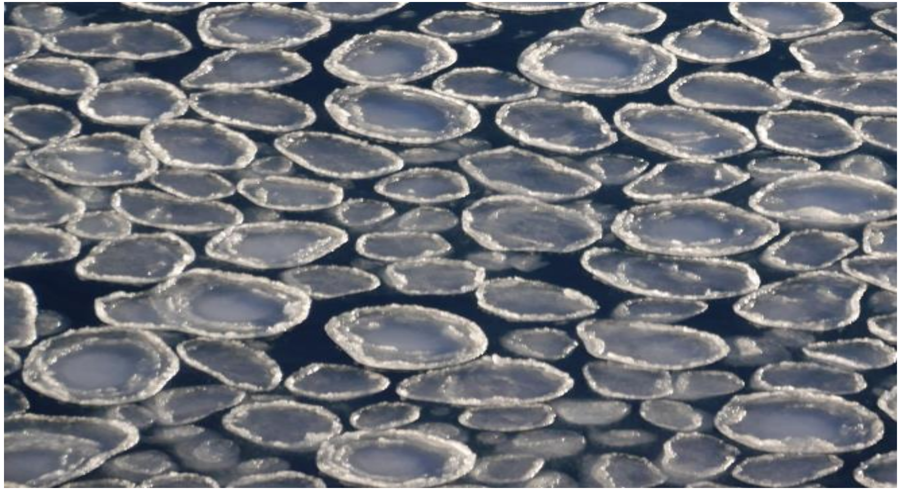
Biological and geochemical proxies for water temperature



MARGO 2009

The Last Glacial Maximum – sea ice

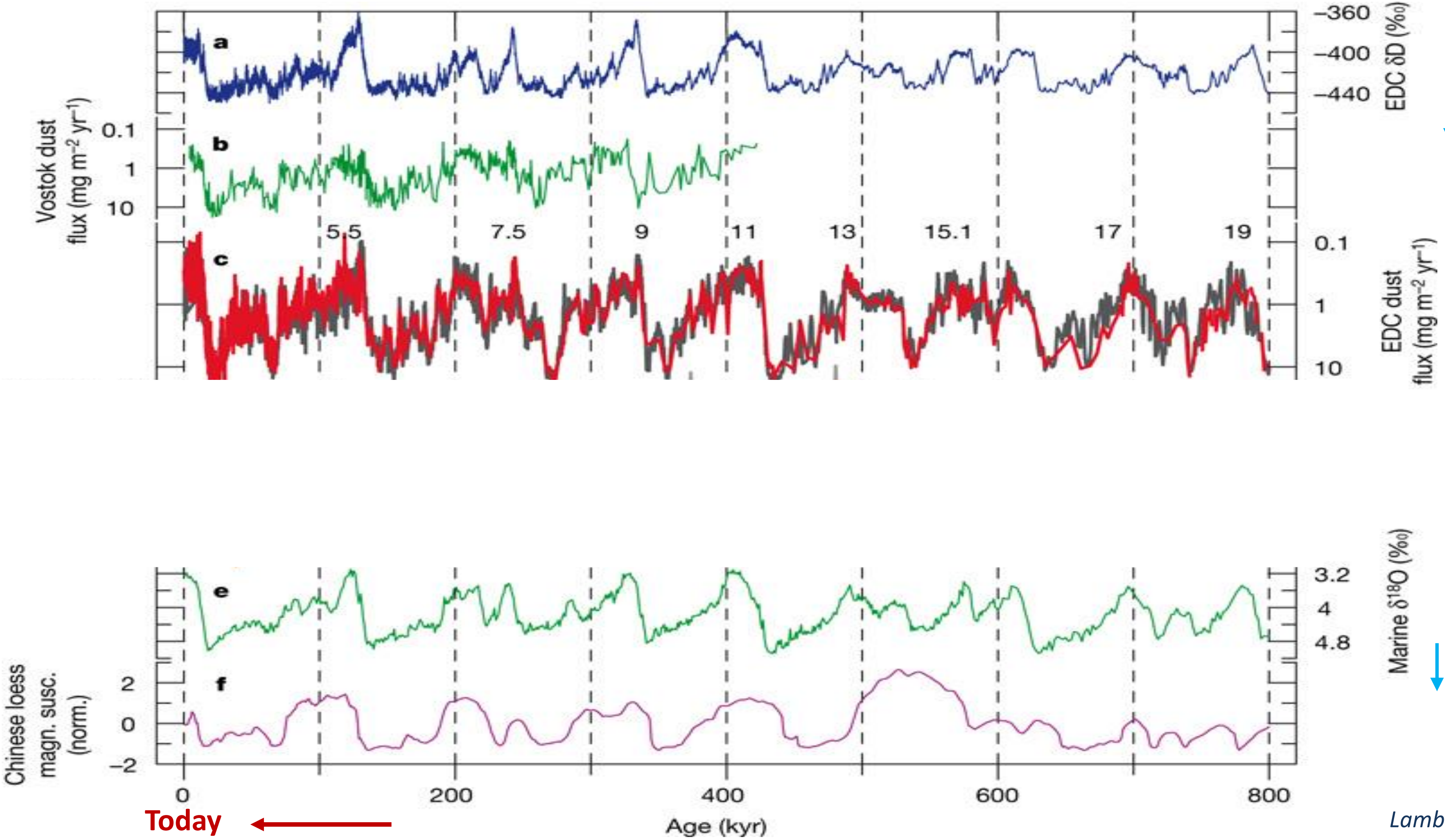
Ruddiman 2014



Frozen ocean water

Photos: S.Greenwood

The Last Glacial Maximum – aridity & winds



Temp.

↓ colder

Dust, Antarctica

↓ dustier

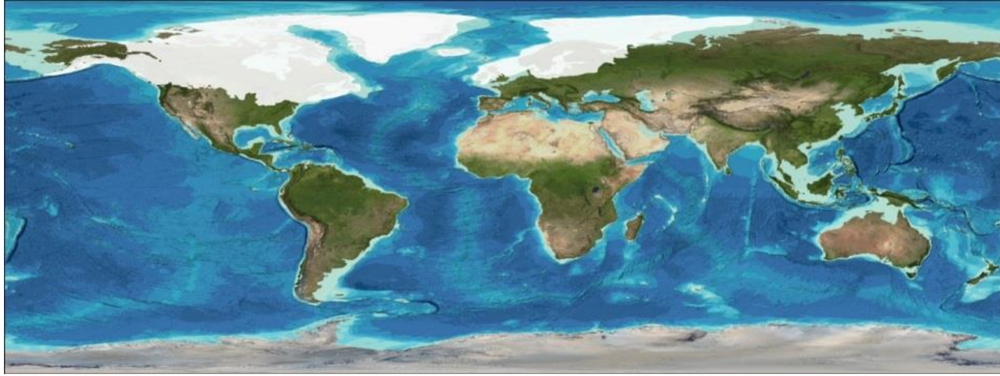
Ice volume

↓ more ice

Loess, China

Lambert et al 2008

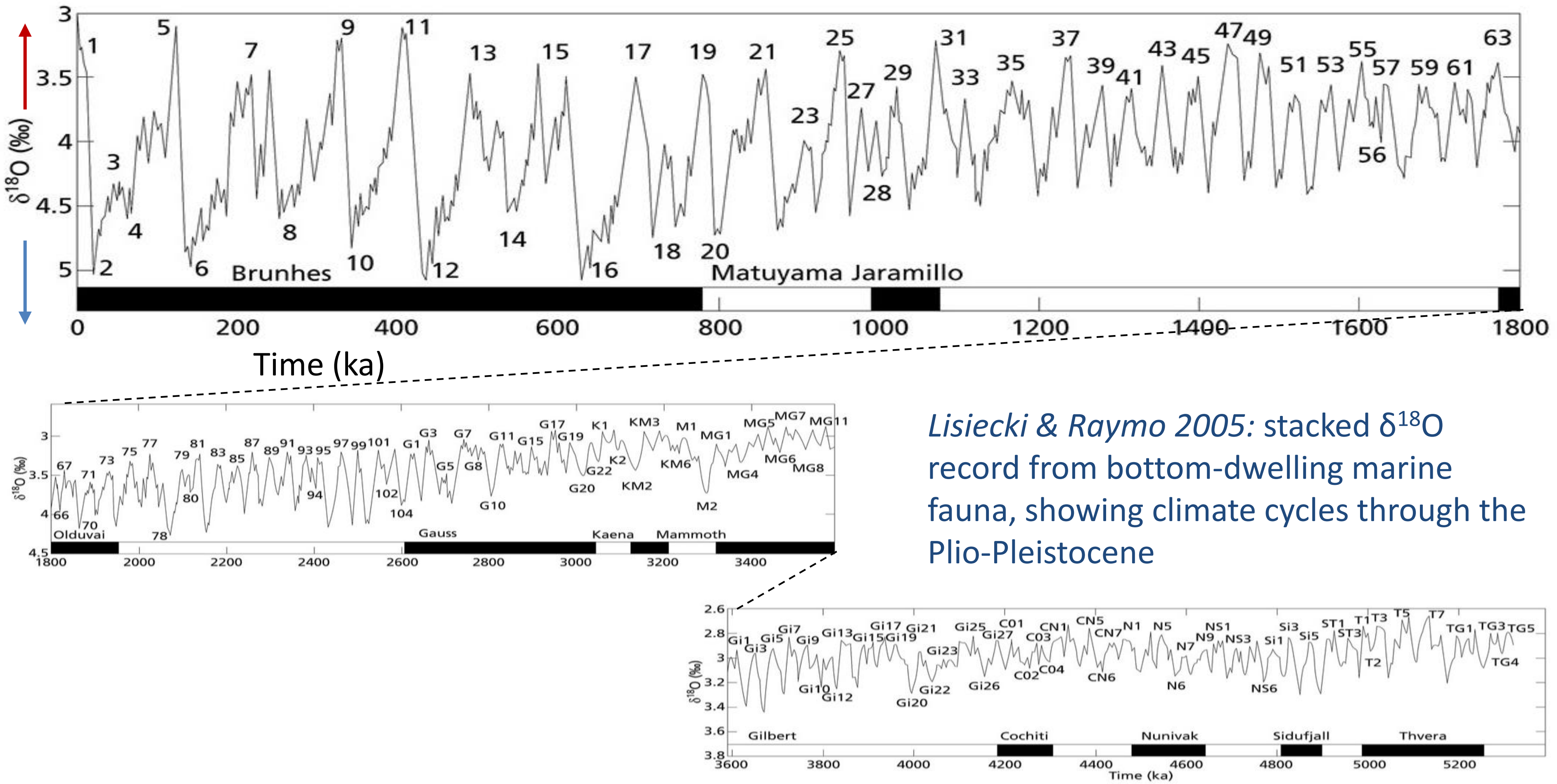
The Last Glacial Maximum



- Large mid-latitude ice sheets
- Sea level fall ~125 m
- Isostatic response of land to loading
- Expanded sea ice
- Increased winds
- *Shifts in vegetation belts; changes to supply of freshwater to oceans; changes in atmosphere-ocean exchange; changes to atmosphere & ocean circulation*

Changes have been cyclical, over 10s of thousands of years

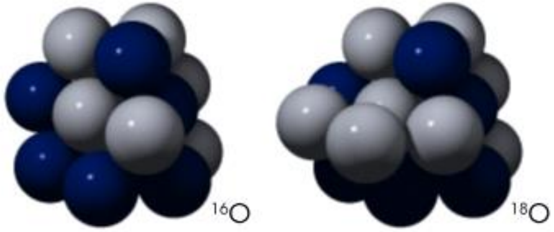
Glacial-interglacial cycles – Plio-Pleistocene climate change



Lisiecki & Raymo 2005: stacked $\delta^{18}O$ record from bottom-dwelling marine fauna, showing climate cycles through the Plio-Pleistocene

Glacial-interglacial cycles – Plio-Pleistocene climate change

from NASA



^{18}O has two additional neutrons than ^{16}O –> heavier.

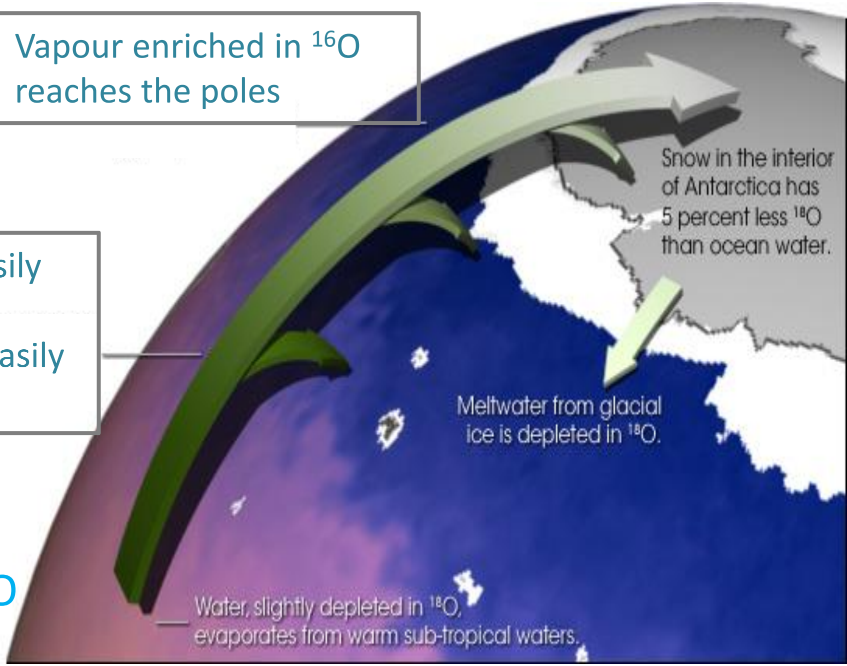
In glacial periods, ^{16}O is locked into ice sheets

Vapour enriched in ^{16}O reaches the poles

Warm water favours ^{16}O fixation into marine shells:
warm temperature -> lower marine δ^{18}O

^{16}O (light) easily evaporates
^{18}O (heavy) easily rains out

Ice volume locks ^{16}O in the ice sheets, and leaves the oceans enriched in ^{18}O: more ice -> higher marine δ^{18}O

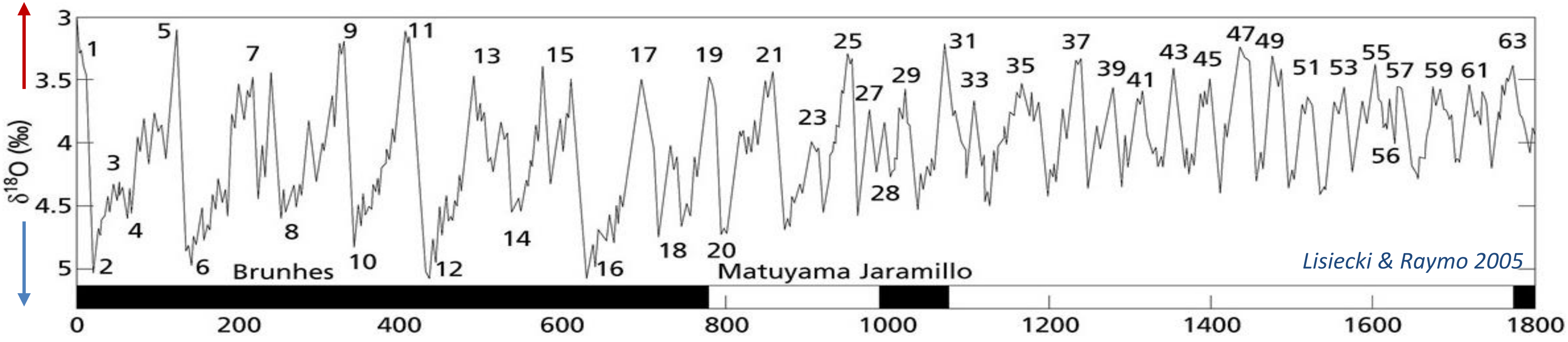


from NASA

Ocean δ^{18}O is a product of ***ice volume*** and ***temperature***

Glacial-interglacial cycles – Plio-Pleistocene climate change

Warmer ***and less ice volume***



Lisiecki & Raymo 2005

Colder ***and more ice volume***

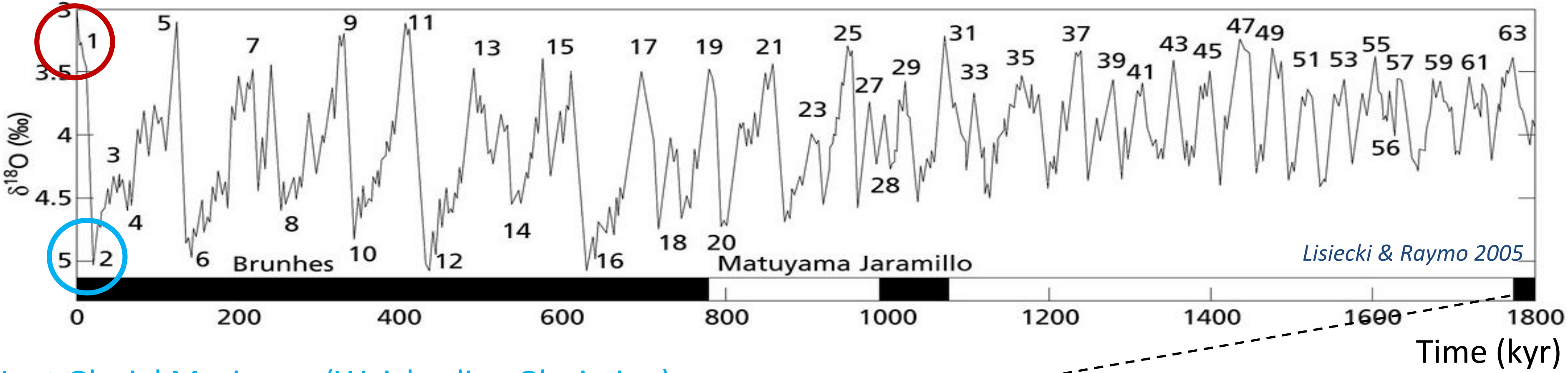
$\delta^{18}O$ is a product of ***ice volume*** and ***temperature***

We use the benthic $\delta^{18}O$ marine record as the best proxy for global ice volume

→ large oscillations in global ice volume throughout the Plio-Pleistocene

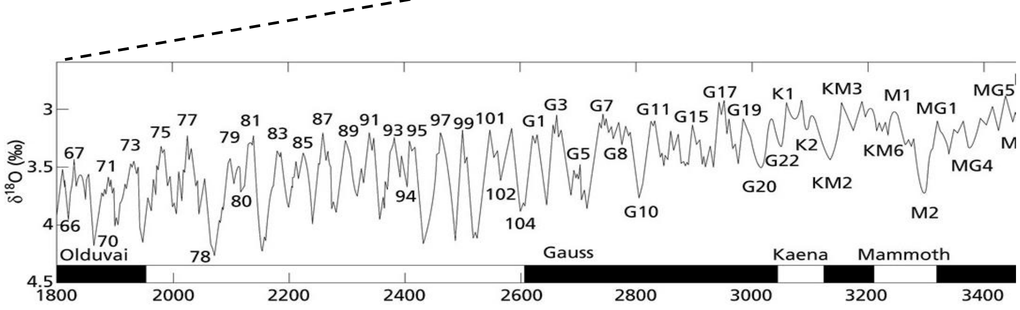
Glacial-interglacial cycles – Plio-Pleistocene climate change

Present interglacial (Holocene)



Lisiecki & Raymo 2005

Last Glacial Maximum (Weichselian Glaciation)

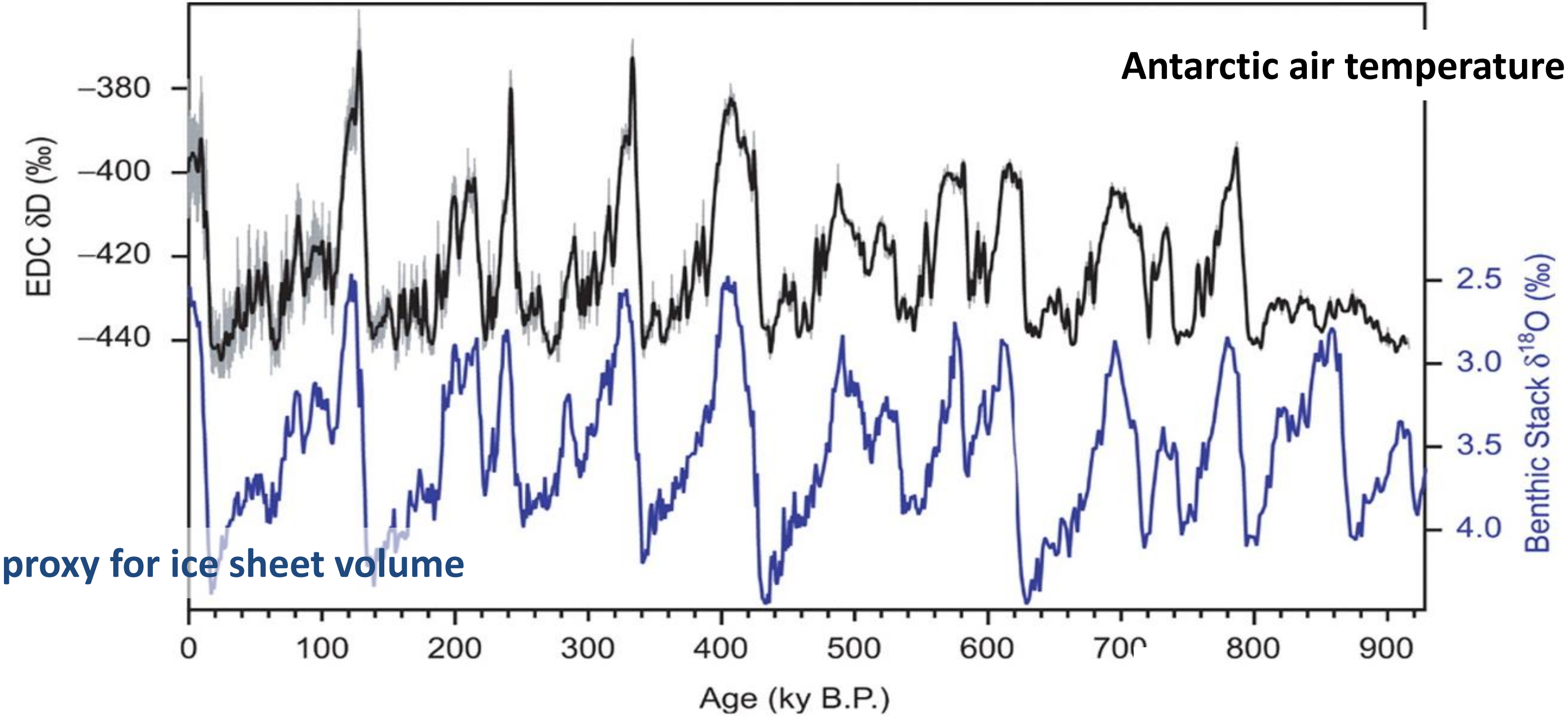


Marine record shows ~50 glacial-interglacial cycles through the Pleistocene

Numbered 'Marine Isotope Stages'

- ***even*** numbers are glacials
- ***odd*** numbers are interglacials

Glacial-interglacial cycles – Plio-Pleistocene climate change



Antarctic air temperature proxy

Marine proxy for ice sheet volume

Jouzel et al. 2007

Glacial-interglacial cycles – Cenozoic climate change

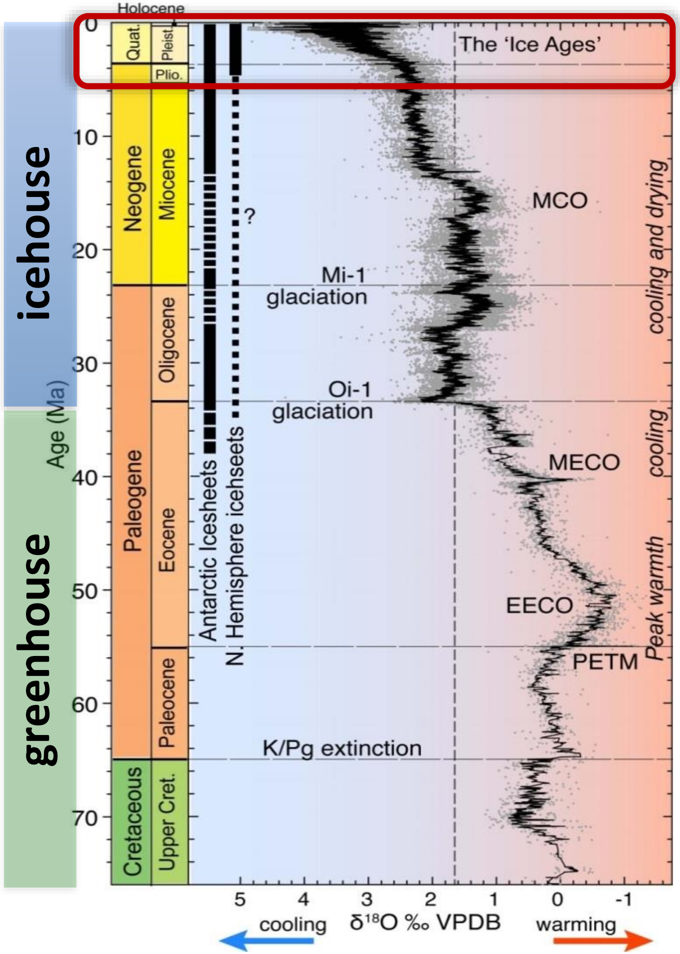


Fig. after Zachos et al. 2008

-> repeated glaciation characterises the Plio-Pleistocene, with major expansion of ice sheets in the northern hemisphere ~3 Ma

.

.

.

.

Antarctic ice sheet established at the Eocene-Oligocene (EO) boundary

.

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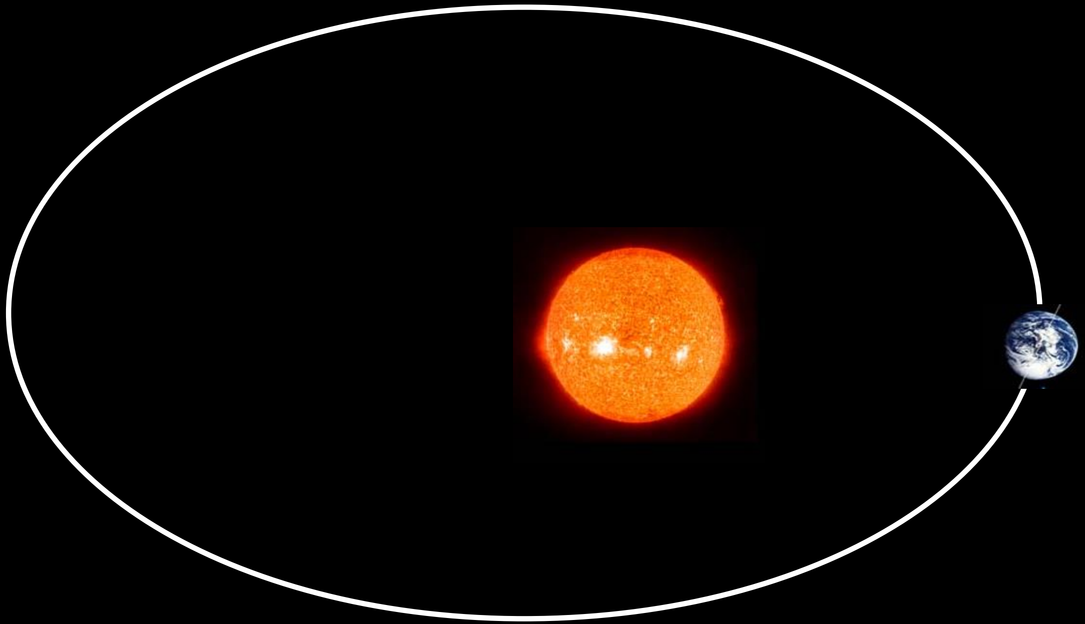
Gradual decline from greenhouse to icehouse world

What has caused cyclic glacial-interglacial climate change?

Orbital forcing of glacial-interglacial climate cycles



Energy that drives the climate system: the Sun.

Changes in the way that Earth receives solar energy (insolation) should affect climate

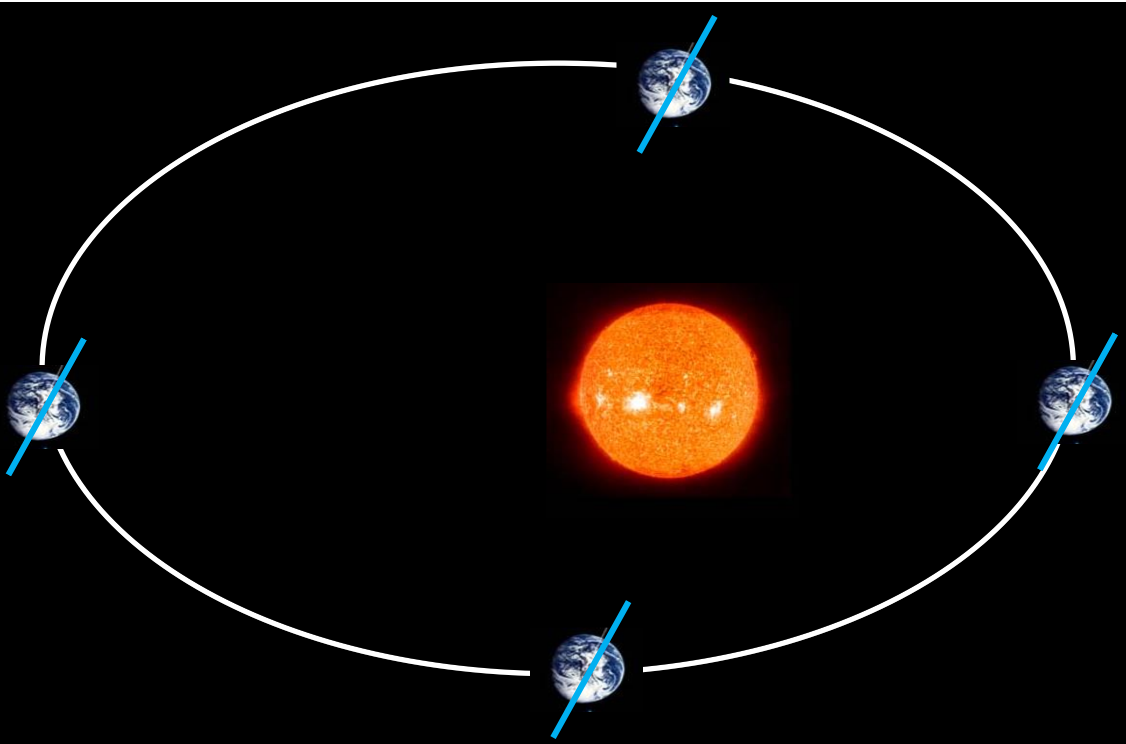
Three parameters of Earth’s orbit:

Tilt of Earth’s axis (obliquity)

Eccentricity of the orbit

Precession of the equinoxes

Orbital forcing of glacial-interglacial climate cycles



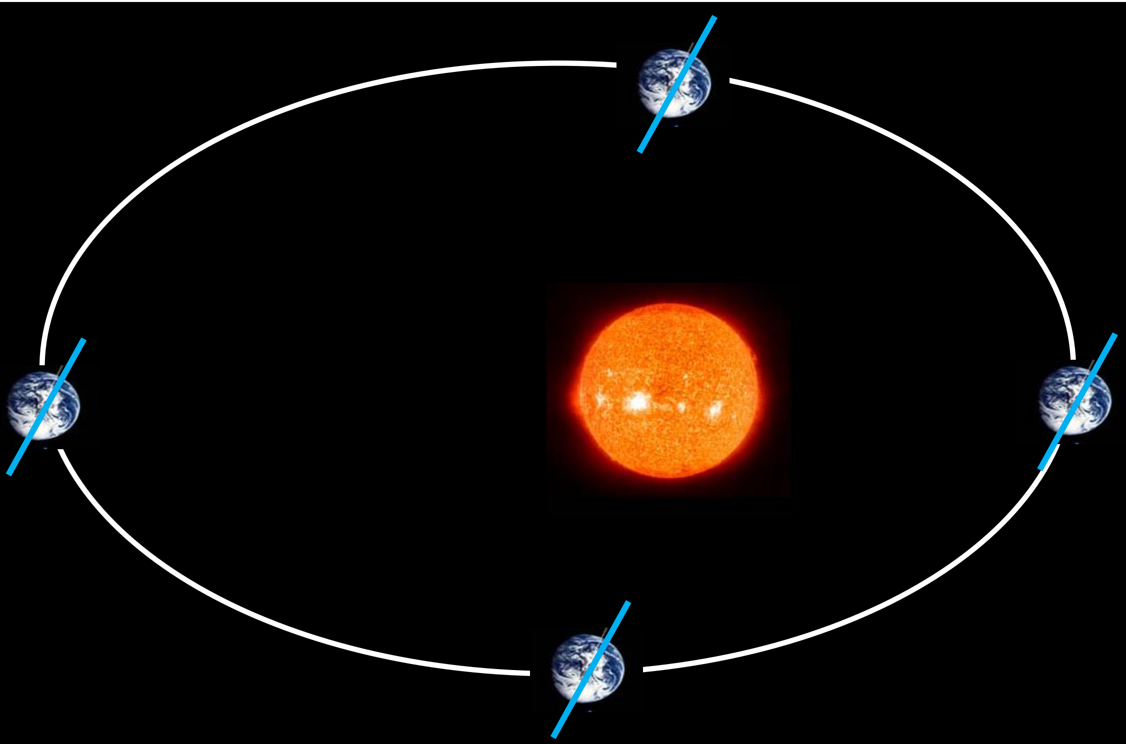
Tilt:

Angle of Earth’s axis tilts at 23.5°

Responsible for latitudinal distribution of sun’s energy: equator receives more than poles

Responsible for seasons: the hemisphere tilted towards the Sun receives more direct sunlight

Orbital forcing of glacial-interglacial climate cycles

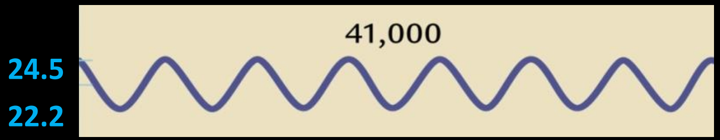


Tilt:

The angle of tilt varies over time, between 22.2° and 24.5°

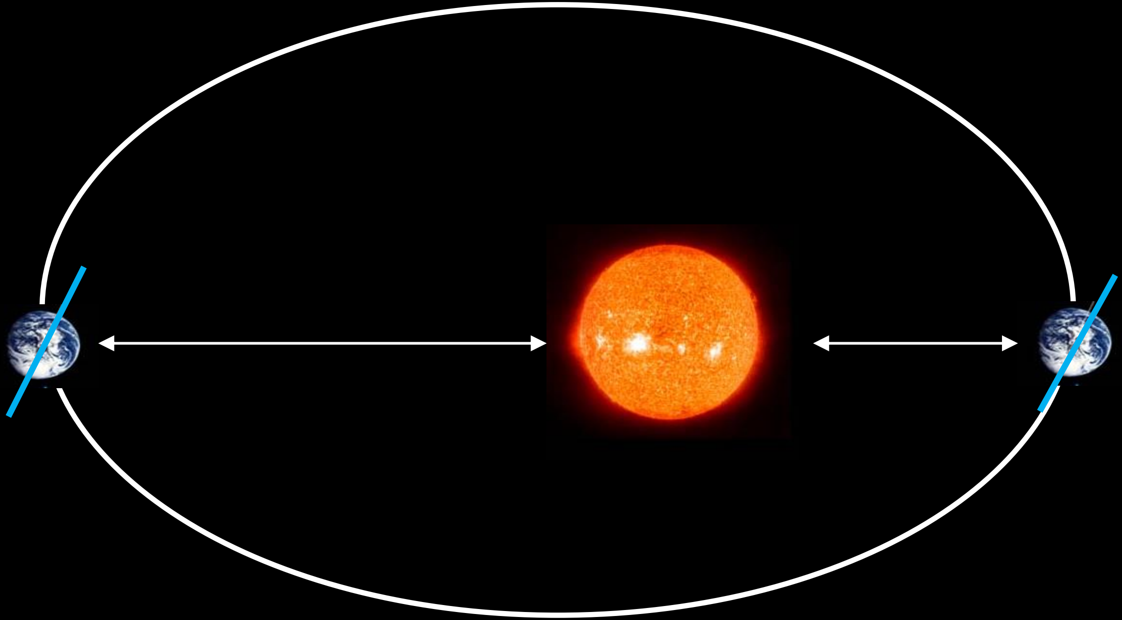
Low tilt (closer to vertical)
-> more uniform hemispheric dist'n
-> less intense seasons

High tilt (closer to horizontal)
-> greater hemispheric difference
-> more intense seasons



41,000 year cycle

Orbital forcing of glacial-interglacial climate cycles

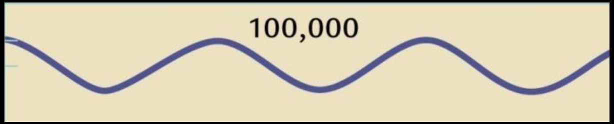


Eccentricity:

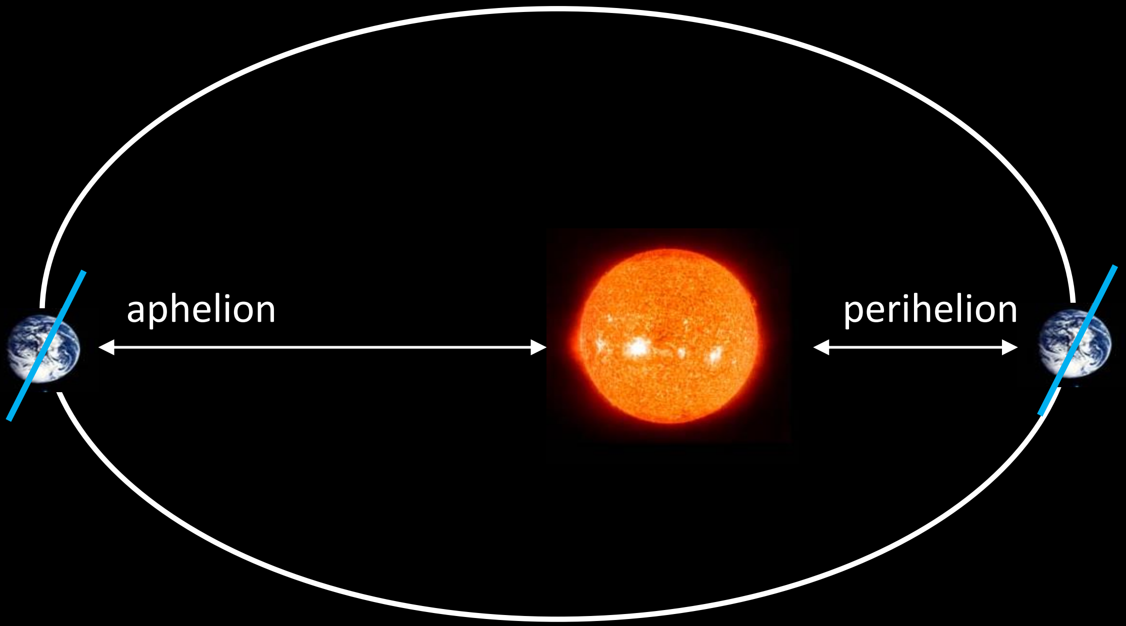
Earth’s orbit is an ellipse

Varies over time from more circular to more elliptical

100,000 year cycle



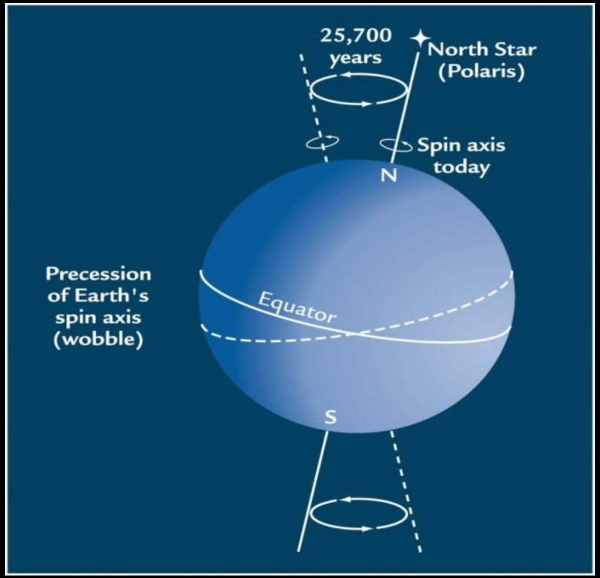
Orbital forcing of glacial-interglacial climate cycles



Precession:

The ***direction*** of the Earth's axis 'wobbles' (precession of the axis)

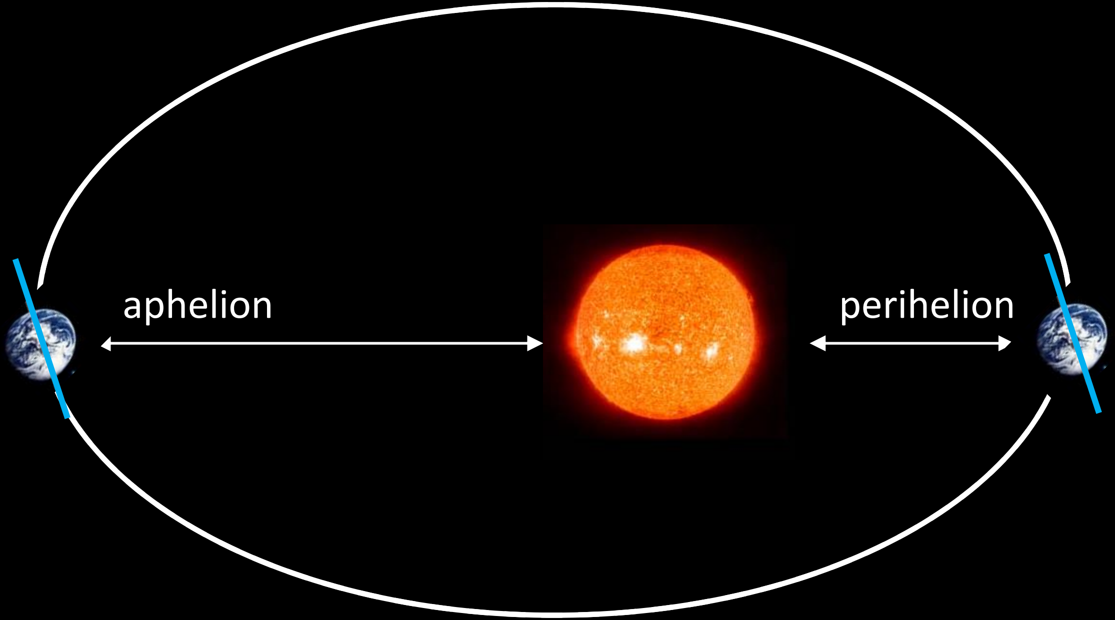
Ruddiman 2014



Today: NH winter solstice is close to perihelion -> mild seasons

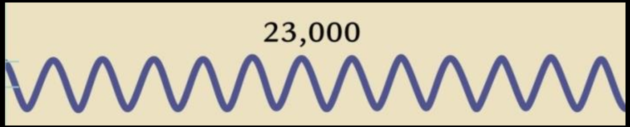
When the direction of tilt changes:
NH winter at aphelion -> intense seasons

Orbital forcing of glacial-interglacial climate cycles



Precession:

The ***direction*** of the Earth's axis 'wobbles' (precession of the axis)

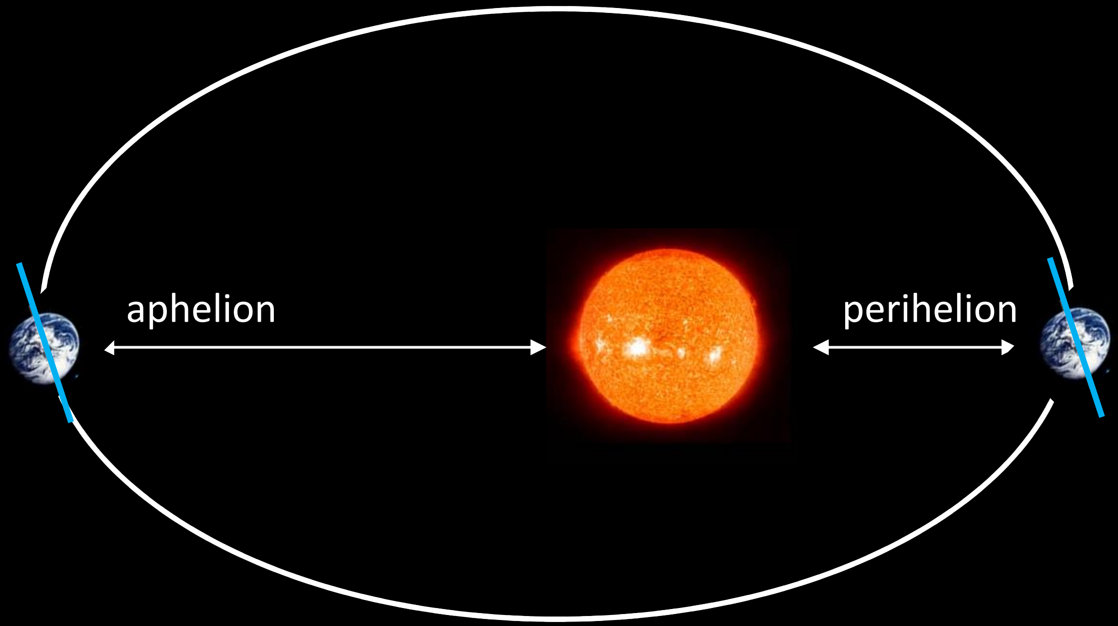


(19-)23,000 year cycle

The orbit itself also revolves… (precession of the ellipse)

In combination, these cause the position of the equinoxes & solstices to move around the orbit.

Orbital forcing of glacial-interglacial climate cycles

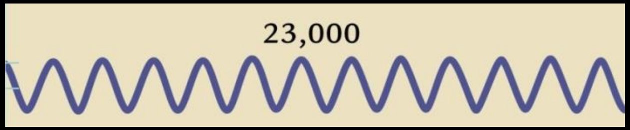


Eccentricity modulates the effect of precession.

More circular: precession effects dampened
More elliptical: precession effects enhanced

Precession:

The ***direction*** of the Earth's axis 'wobbles' (precession of the axis)



(19-)23,000 year cycle

Orbital forcing of glacial-interglacial climate cycles

Early hypothesis: changes in insolation received by Earth, resulting from changes in orbital geometry, were responsible for the widespread growth of northern hemisphere ice sheets

Which season is most important?

- Winter?
- Summer?

Milutin Milanković (1920s) +
Alfred Wegener, Wladimir Köppen

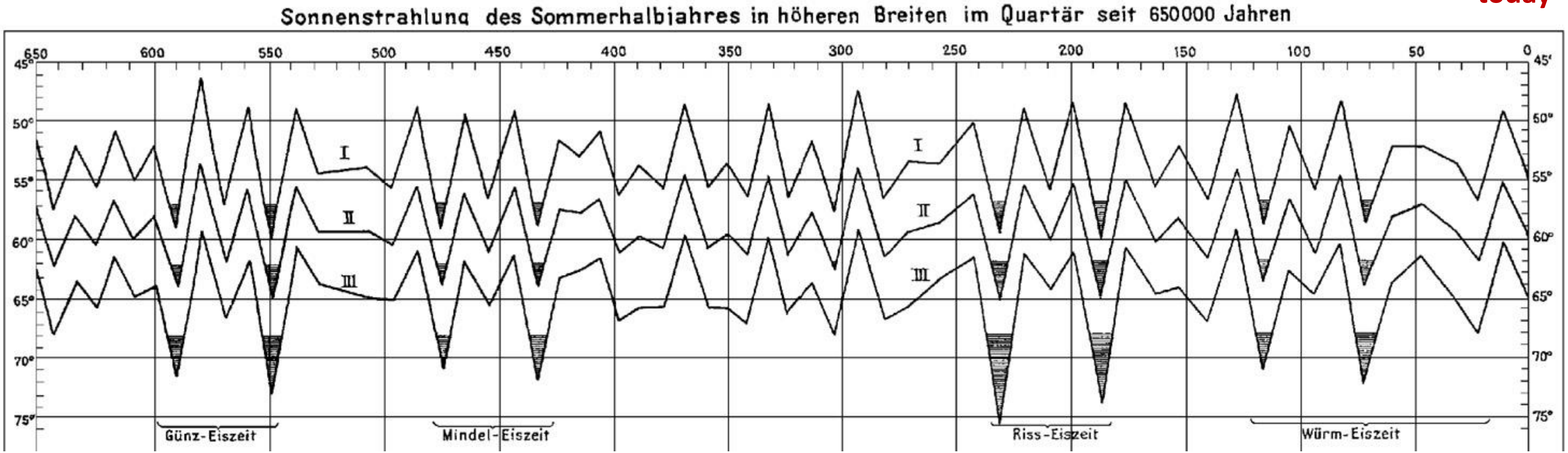
Argued that ***summer insolation controls ice sheet growth and decay***

Orbital forcing of glacial-interglacial climate cycles

Summer insolation

Milanković's summer insolation curves, published in Köppen & Wegener 1924

→ **today**



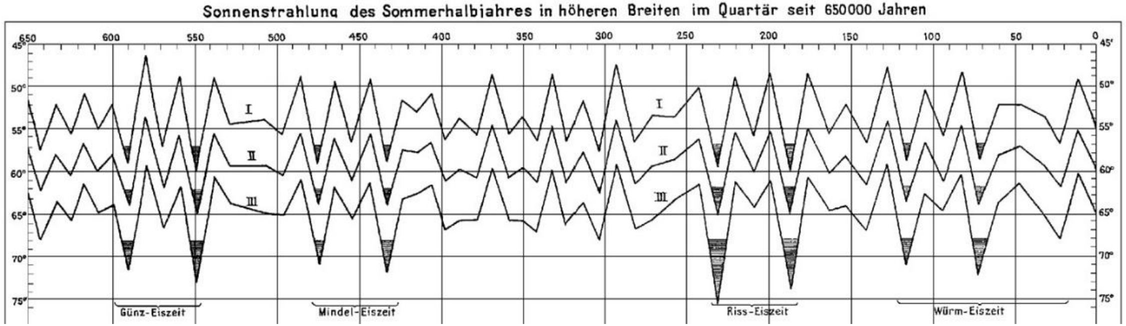
Sonnenstrahlung des Sommerhalbjahres in höheren Breiten im Quartär seit 650000 Jahren

Orbital forcing of glacial-interglacial climate cycles

Ice-age cycles solved?

- Radiometric dating of geological deposits
- Erosion of evidence by subsequent glaciation

BBC Frozen Planet

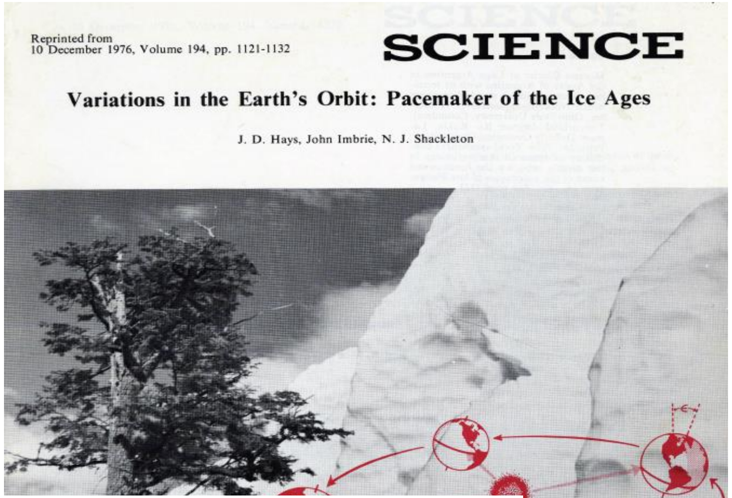


Orbital forcing of glacial-interglacial climate cycles

Hays, Imbrie & Shackleton, 1976.

"…changes in the earth's orbital geometry are the fundamental cause of the succession of Quaternary ice ages."

Frequency analysis of long records of benthic oxygen isotopes (ice volume):



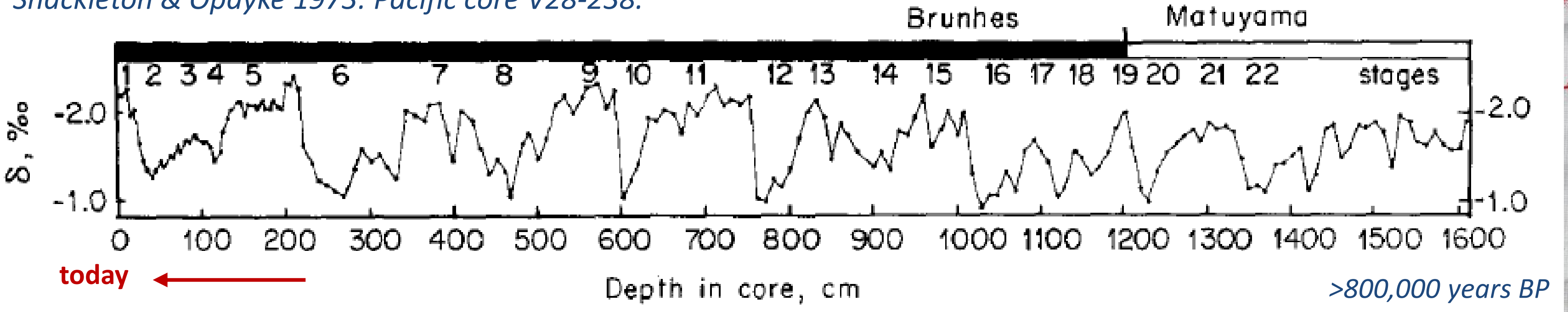
Reprinted from
10 December 1976, Volume 194, pp. 1121-1132

SCIENCE

Variations in the Earth's Orbit: Pacemaker of the Ice Ages

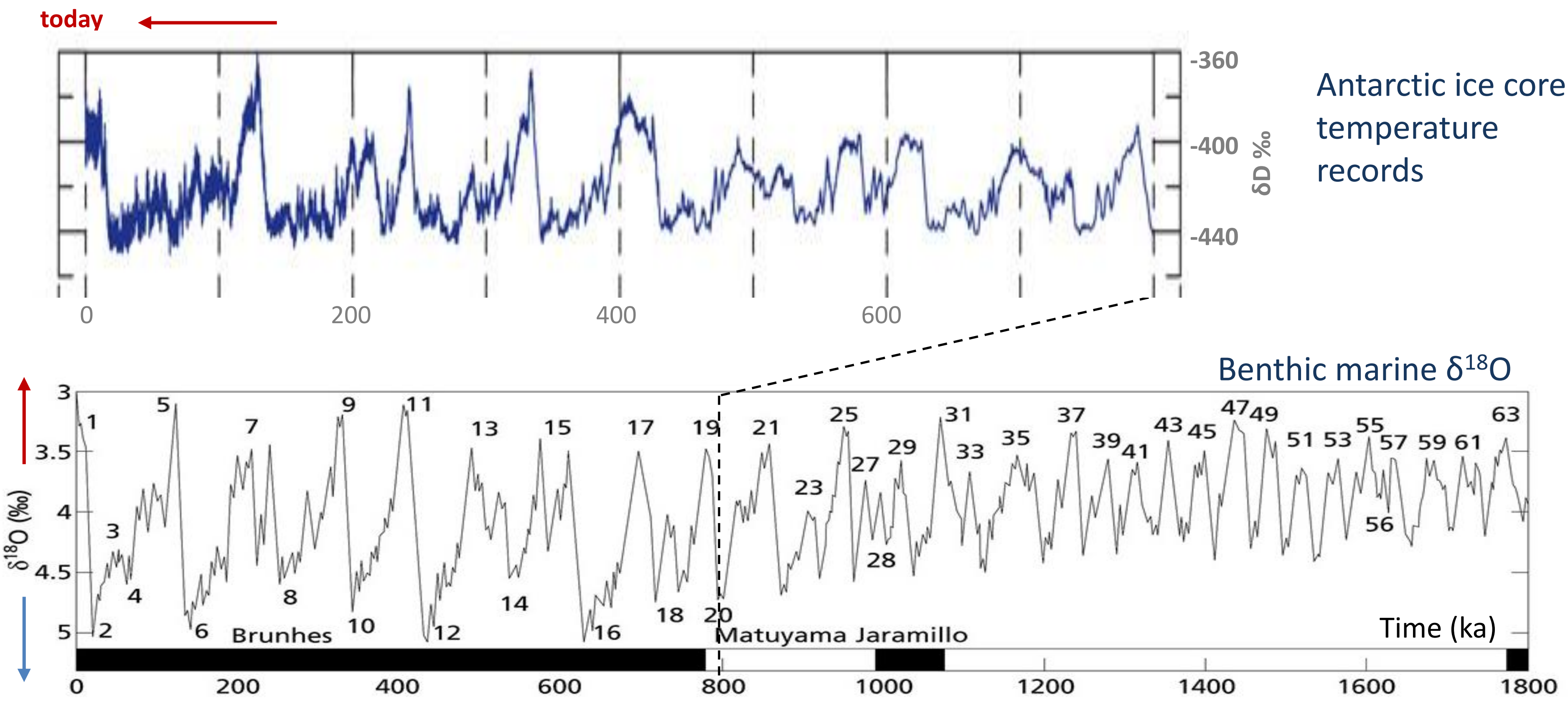
J. D. Hays, John Imbrie, N. J. Shackleton

Shackleton & Opdyke 1973: Pacific core V28-238.



Frequencies corresponding to orbital frequencies (100 kyr, 41 kyr and ~23 kyr) dominate the record of ice volume changes on Earth.

Orbital forcing of glacial-interglacial climate cycles



100,000 year cycles

41,000 year cycles

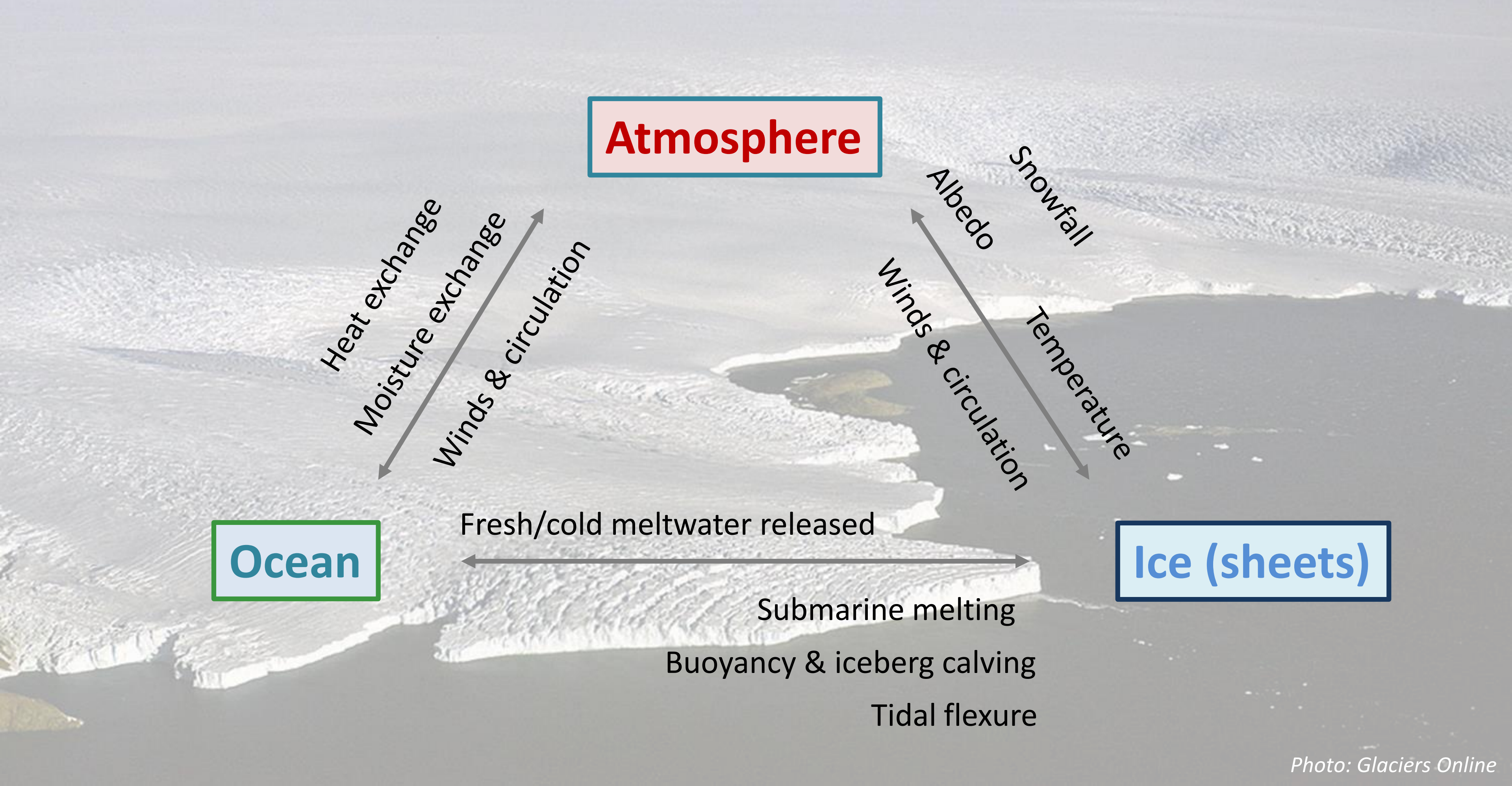
Orbital forcing of glacial-interglacial climate cycles

Variations in Earth’s orbit are the fundamental driver of glacial-interglacial cycles of climate change.

We are currently in a mode in which one glaciation + one interglacial ~100 kyr.

- How does the Earth system (ice sheets, oceans, atmosphere, lithosphere…) respond to insolation forcing?
- Why did Earth shift from a dominant 41kyr cycle response to the 100kyr cycle?
- Why are the (100kyr) cycles asymmetric: slow build-up and rapid terminations (deglaciation)?
- How might ice sheets themselves influence global climate cycles?
- Are ice sheets facing renewed growth or imminent collapse?

The ice – ocean – climate system



Atmosphere

Heat exchange

Moisture exchange

Winds & circulation

Albedo

Snowfall

Winds & circulation

Temperature

Ocean

Fresh/cold meltwater released

Ice (sheets)

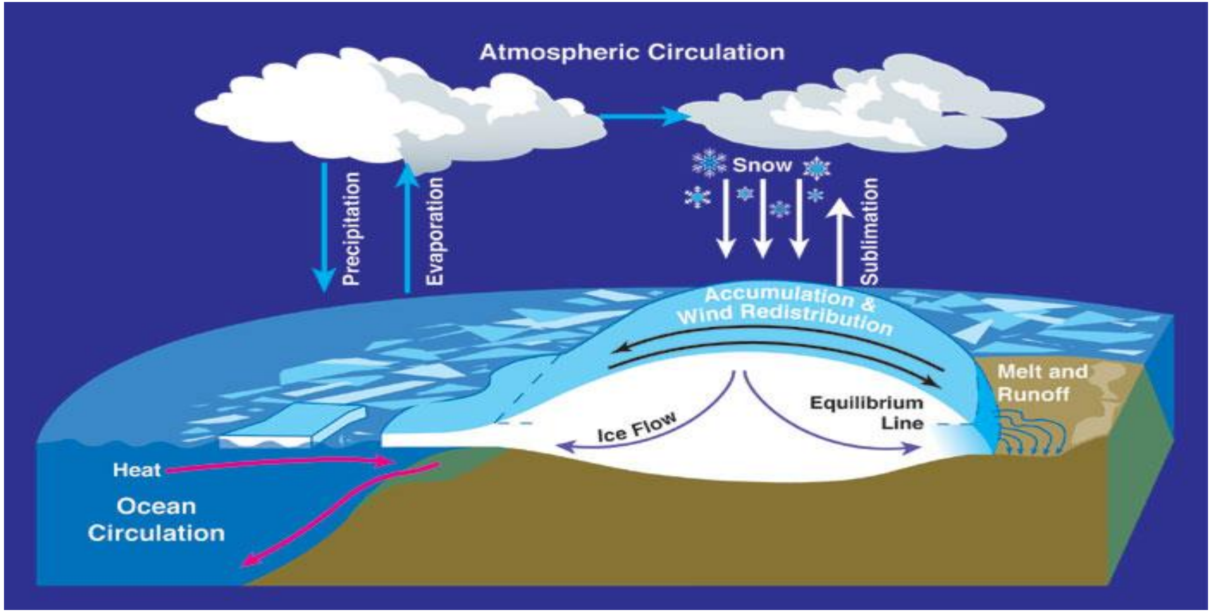
Submarine melting

Buoyancy & iceberg calving

Tidal flexure

Photo: Glaciers Online

The ice – ocean – climate system



NASA / antarcticglaciers.org / wikimedia commons

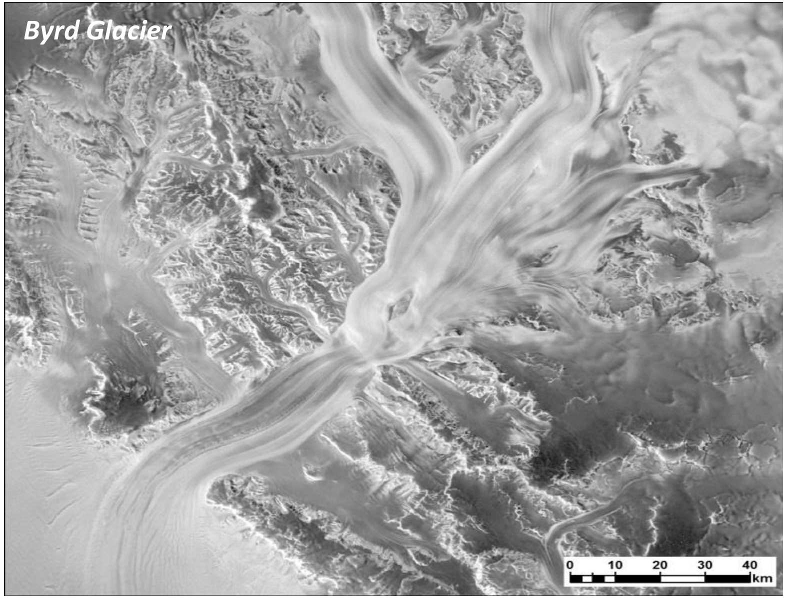
Snow accumulates, and converts to ice under its own pressure

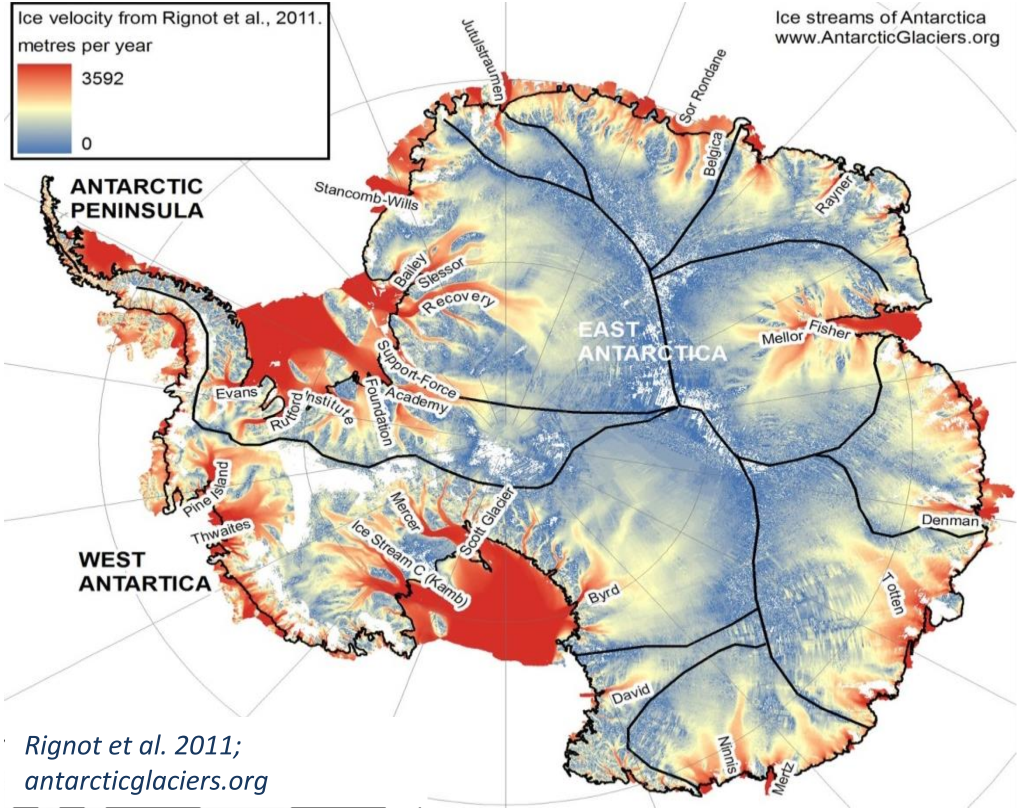
Once thick enough, it begins to flow due to its own weight and due to gravity

Spreads from where it is high to where it is low (where it melts)

Ice sheet volume is governed by snowfall and melting…
and iceberg calving
-> interacts with the atmosphere
-> interacts with the ocean

The ice – ocean – climate system





Rignot et al. 2011; antarcticglaciers.org

Flow rates, in response, are highly variable

Ice is partitioned into fast and slow flowing pathways

Deliver ice from zones of net accumulation (ice sheet interior) to zones of net ablation (sea level) – 90% of Antarctic ice sheet discharge via "ice streams"

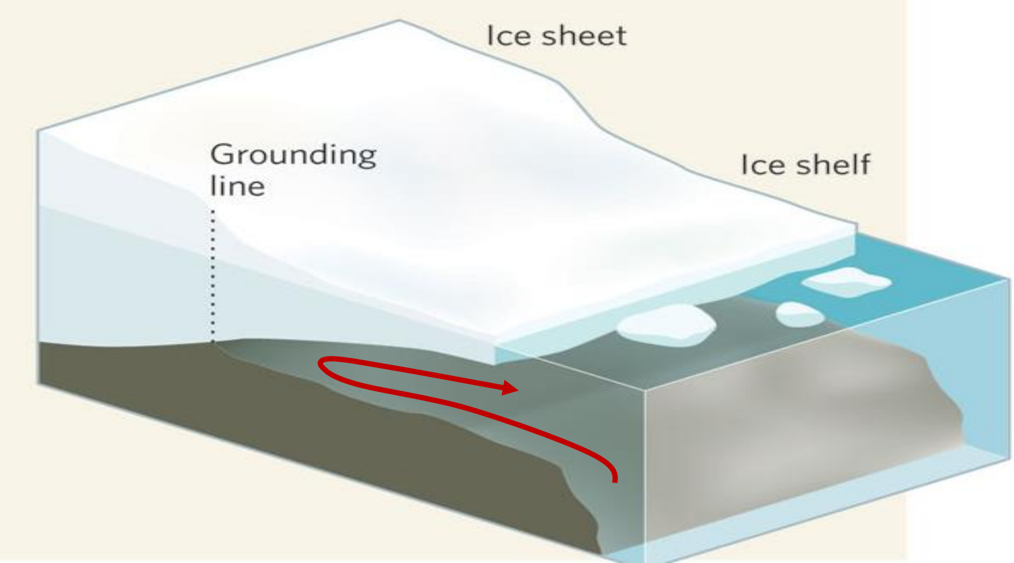
The ice – ocean – climate system

Glaciers Online

Ice shelves fringe ~75% of Antarctica today
- glacier ice that floats on the sea

When ice becomes sufficiently thin (relative to water depth) it will become buoyant

Mass balance of the ice sheet sensitive to ocean processes, as well as "climate" (atmospheric) processes

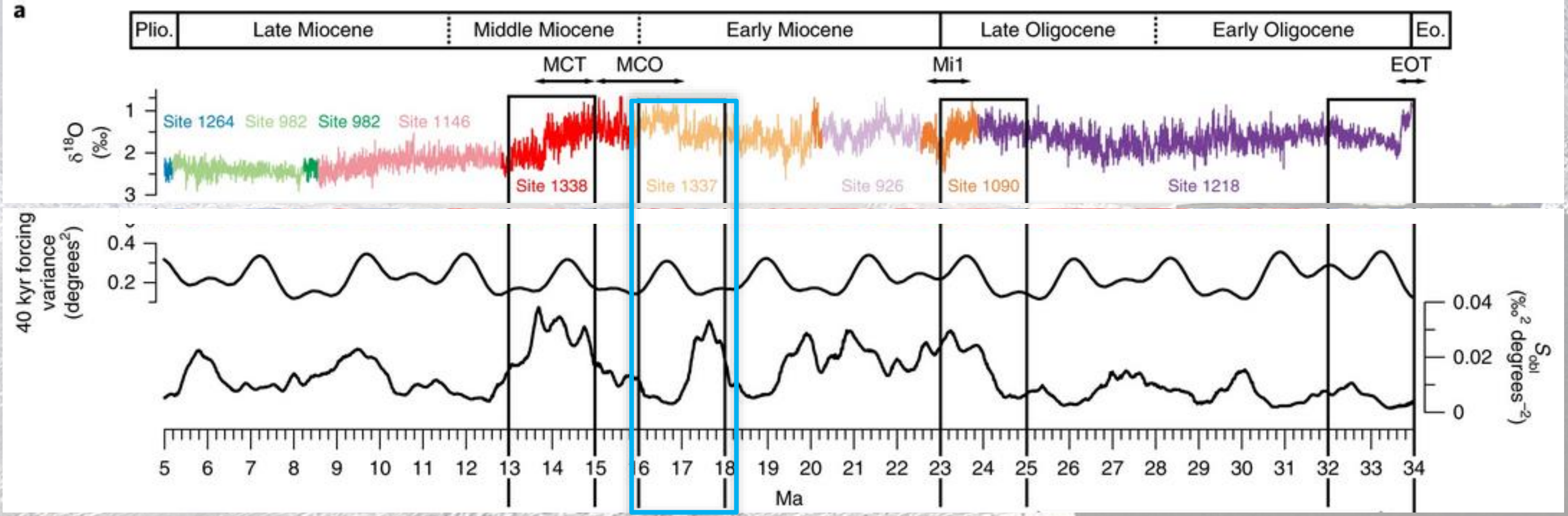


Huybrechts 2009

The ice – ocean – climate system

Levy et al. 2019

Is sensitivity to obliquity greater when ice sheets have marine margins?



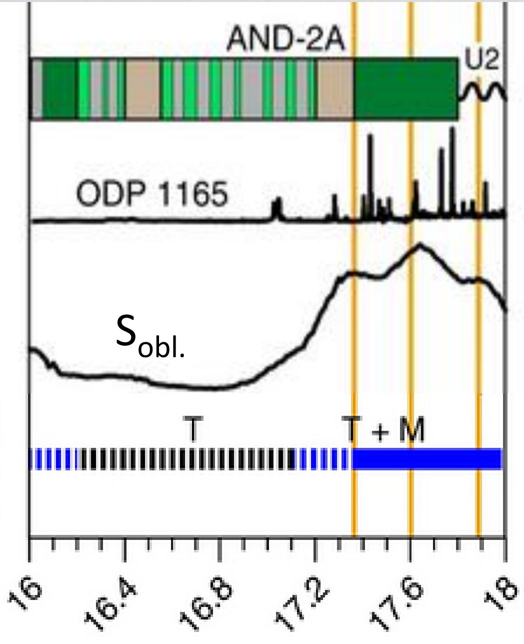
High obliquity -> more energy to high latitudes -> weaker N-S temperature gradient

Consequences for winds & ocean circulation -> warm-water advection onto continental shelf

The ice – ocean – climate system

Levy et al. 2019

Is sensitivity to obliquity greater when ice sheets have marine margins?



Glacial deposits in continental shelf core

Ice-rafted debris (iceberg sediments)

Terrestrial & marine margins / terrestrial-only

Peak expansion into ocean

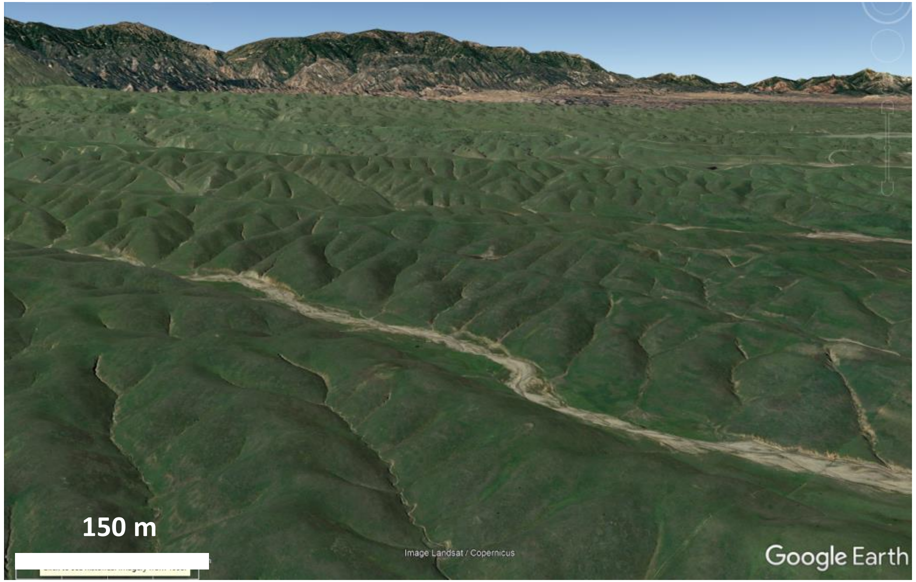
We have had marine margins since the MPT (100 kyr cycles)
- Sea ice suppression of ocean effects?

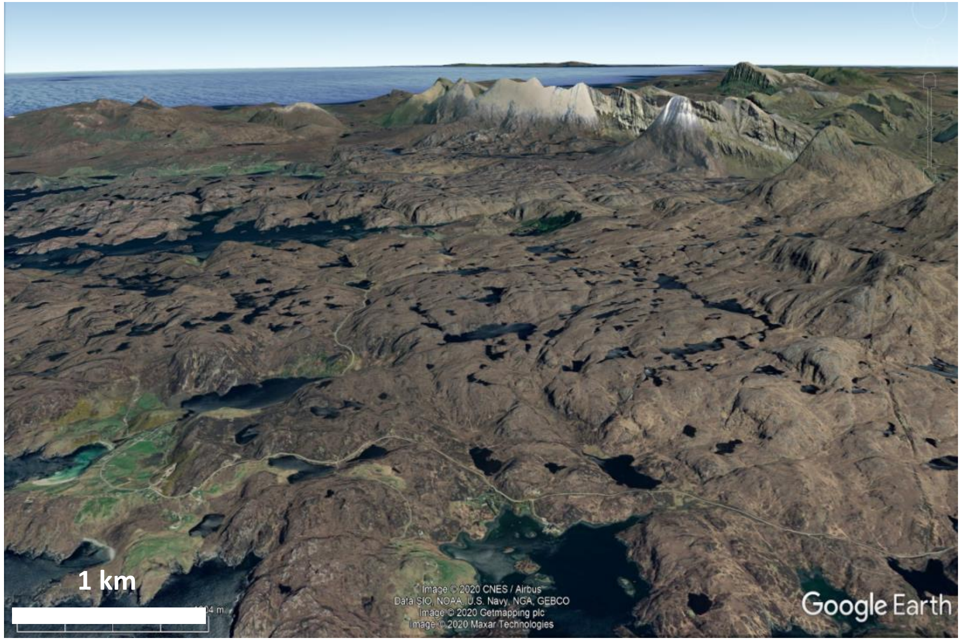
High obliquity -> more energy to high latitudes -> weaker N-S temperature gradient
Consequences for winds & ocean circulation -> warm-water advection onto continental shelf

The ice – ocean – climate system

What caused the mid-Pleistocene shift from obliquity (41 kyr) to eccentricity (100 kyr) cycles?

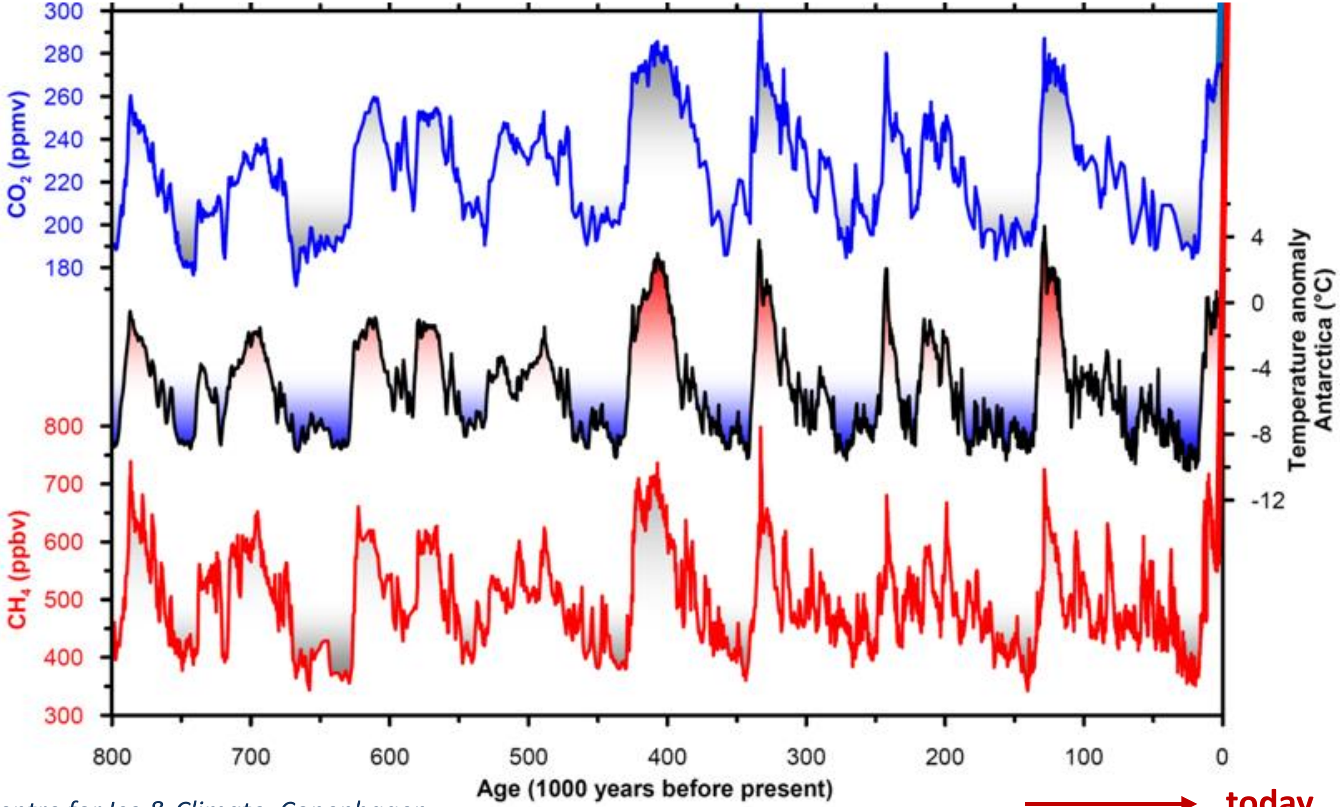
- sea ice feedbacks?
- ice sheet-centred hypotheses vs carbon cycle-centred hypotheses





The ice – ocean – climate system

Role of carbon cycle in orbitally-forced glacial-interglacial cycles?



today

Glacial climates:

- Weaker ocean circulation
- Dust fertilisation of Southern Ocean
- Carbonate weathering on exposed shelves

Challenge:
Ice core from pre-MPT?

Centre for Ice & Climate, Copenhagen

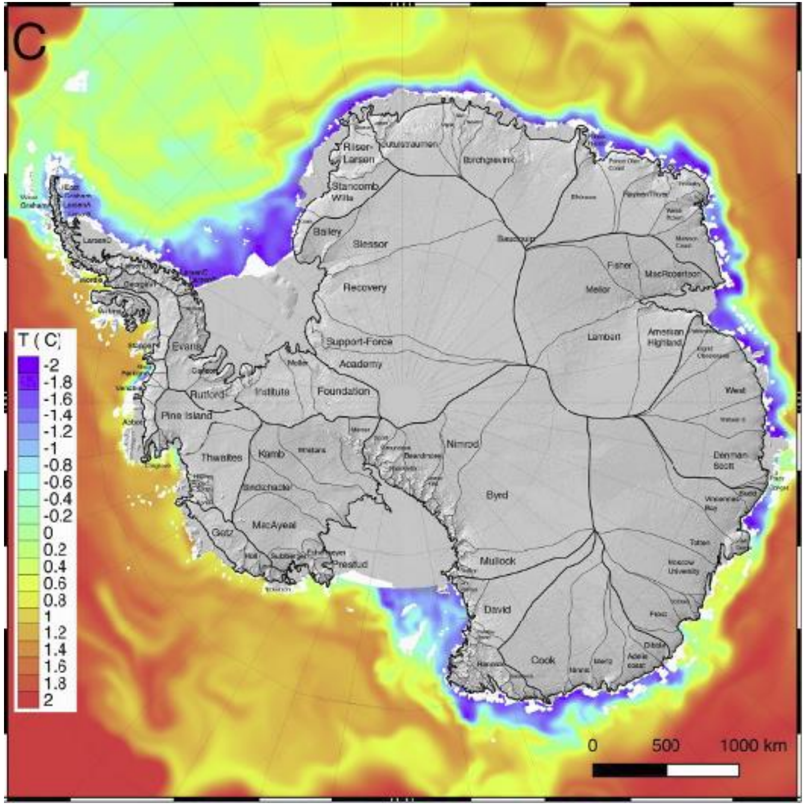
The ice – ocean – climate system

Greenland ice surface
M.Tedesco/Columbia Univ.

Marine ice sheet vulnerability
- insolation-driven surface melt
- ocean-driven submarine melt

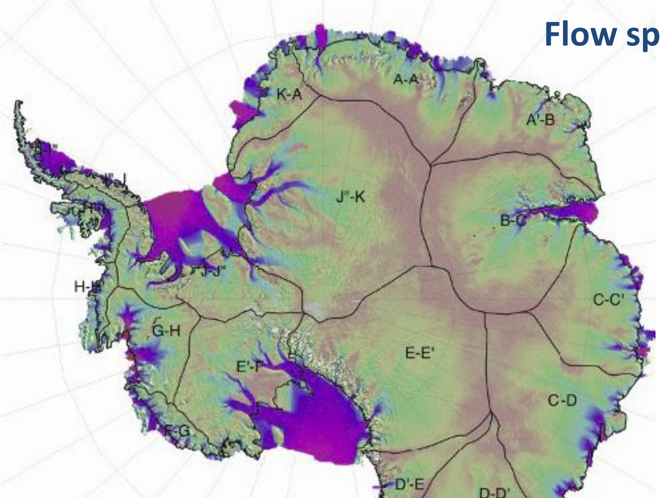
The ice – ocean – climate system

Rignot et al. 2019

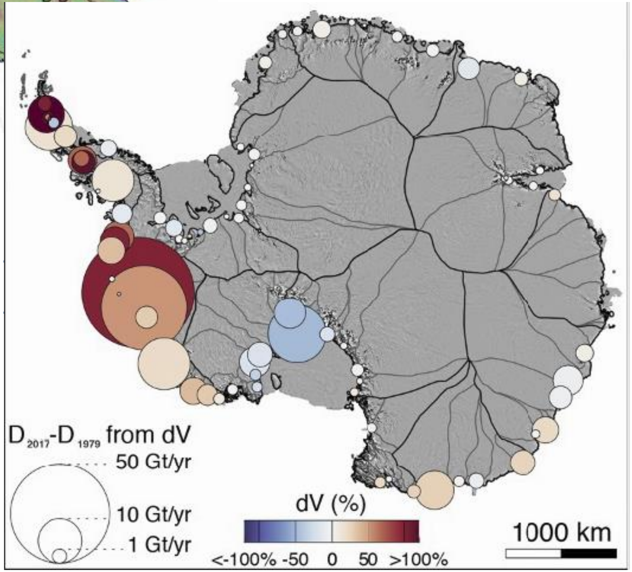


Ocean temperature
(at 300m depth)

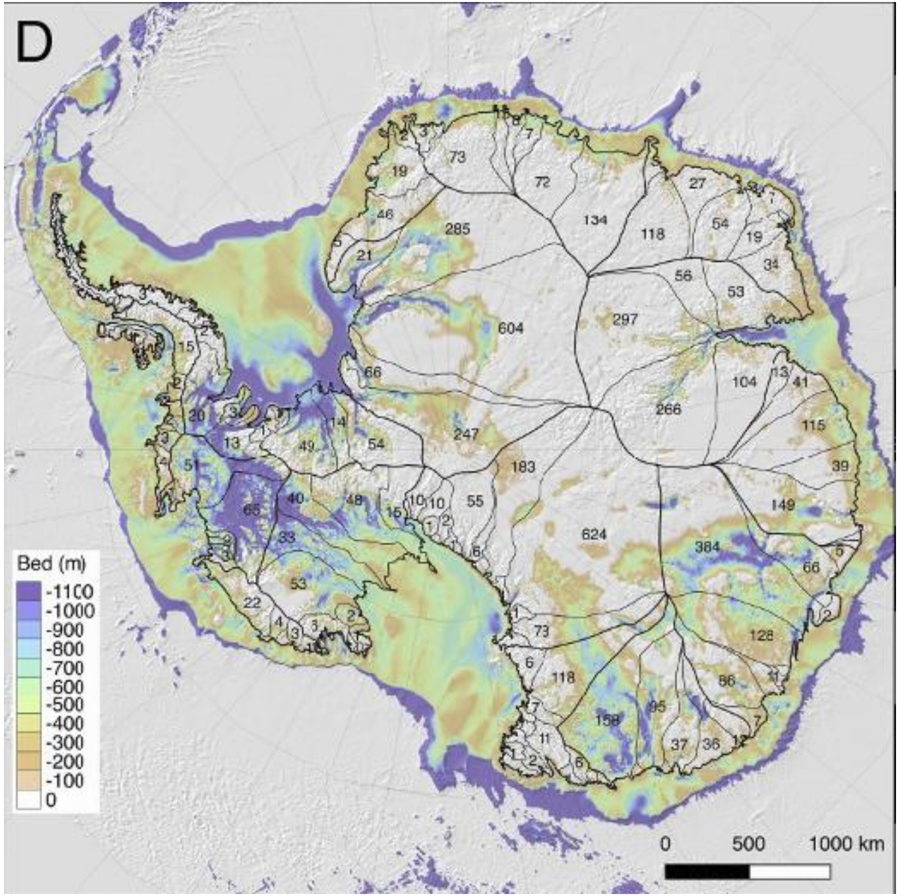
Flow speed

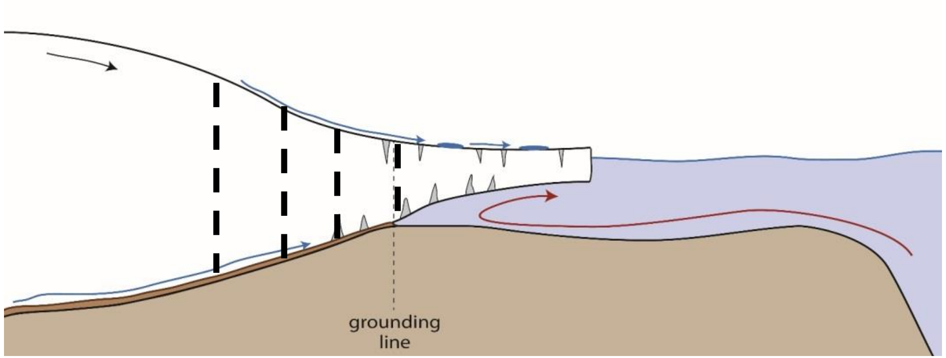


Change in discharge from 1979-2017



The ice – ocean – climate system





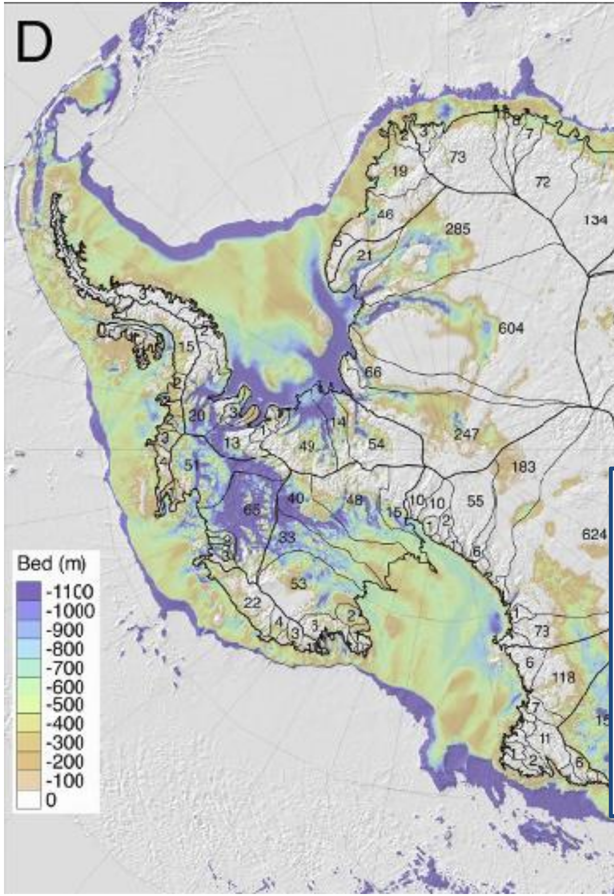
Rignot et al. 2019

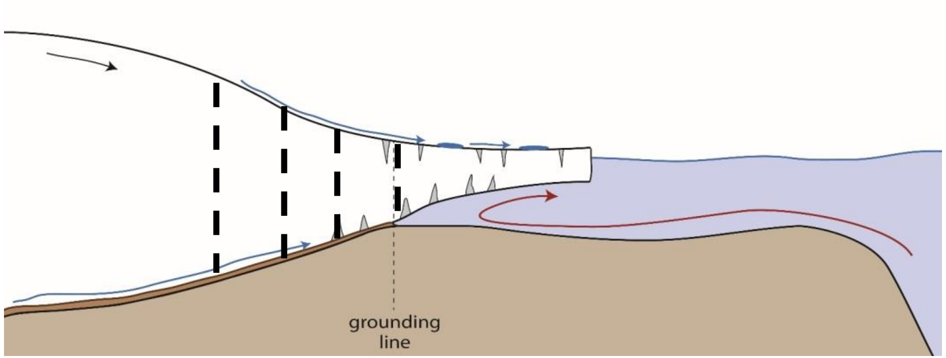
Marine ice sheet vulnerability

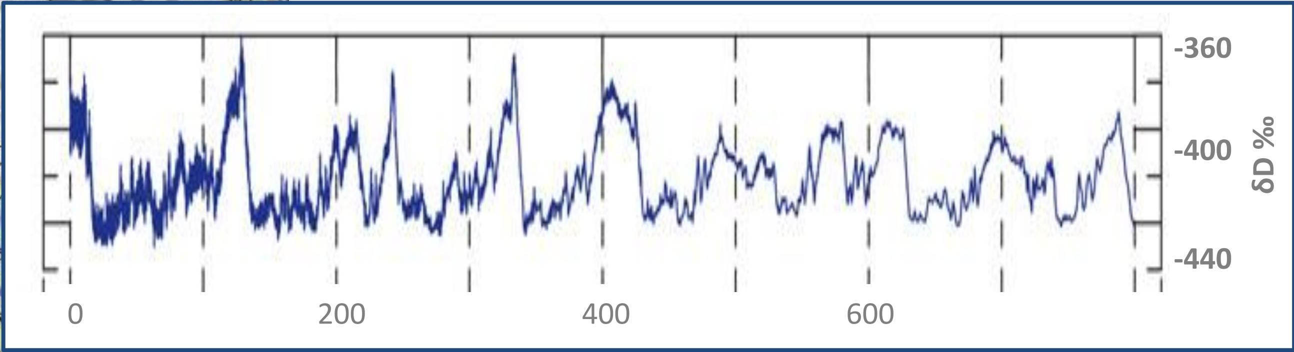
- insolation-driven surface melt
- ocean-driven submarine melt

Inherently unstable on a deepening slope?

The ice – ocean – climate system







Rignot et al. 2019

Summary

Changes to the Earth’s tilt, orbital eccentricity and precession of the equinoxes affects the distribution (& amount) of solar energy received, and drive glacial-interglacial cycles on timescales of tens-of-thousands of years.

Earth’s response is manifest in all parts of the climate system – atmosphere, ocean, ice sheets, biosphere, lithosphere… - and ‘knock-on effects’ are transmitted through the Earth system.

At peaks of glaciation, ice sheets cover northern hemisphere mid-latitudes and expand over Greenland & Antarctica.

Marine-based ice sheets are critically coupled to both atmosphere and ocean. These interactions may explain some characteristics of Earth response to orbital forcing.