(5e)

INSOLATION CONTROL OF ICE SHEET

Source images: Ruddiman, 2007 (Chapter 9)

INTRODUCTION -1

The last 3 Myr

The formation of the Arctic ice sheet around 3 Myr ago may be due to gradual tectonic cooling, but shorter-term changes are likely driven by orbital variations.

The last 20 kyr

kyr ago, ice sheets covered North America and Europe. Since then, the ice has retreated, with the last remnants disappearing around 6 kyr ago.

INTRODUCTION -2

In the Next Slides…

•How summer insolation changes control ice volume

•The lag between orbital forcing (insolation) and climate response (ice cap)

•Isostatic subsidence and rebound due to ice sheet load (bedrock feedback)

•Ice cap variations based on isotope records and corals (last 150 kyr)

•Reconciling Arctic ice sheet evolution with orbital control theory

MILANKOVITCH'S THEORY: ORBITAL CONTROL ON ICE SHEET-1

PERMANENT SNOW LINE

Ice caps can form in areas where snow remains on the ground year-round, even through summer. This occurs when accumulation (total ice mass gained) ≥ ablation (ice loss).

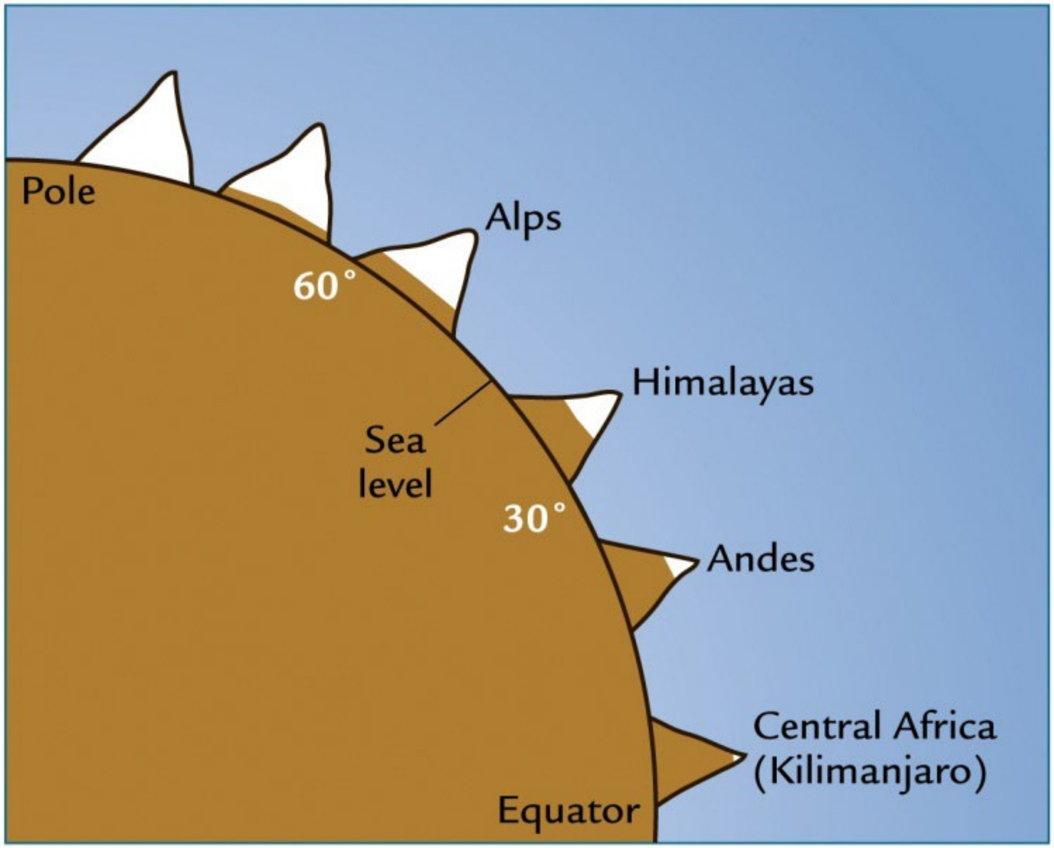
The permanent snow line is the altitude above which annual snow accumulation exceeds ablation, forming part of the cryosphere.

This limit varies by latitude:

Equator: > 5000 m

Poles: ≈ 0 m

Italy: ≈ 3000 m



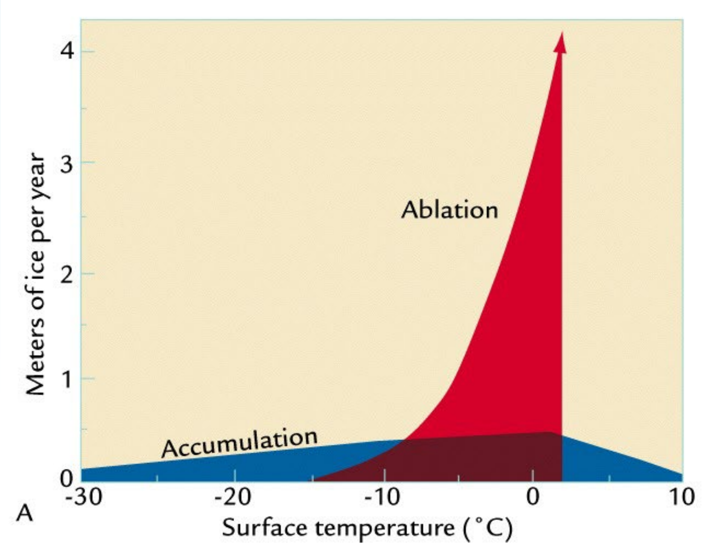
MILANKOVITCH'S THEORY: ORBITAL CONTROL ON THE SHEET -2

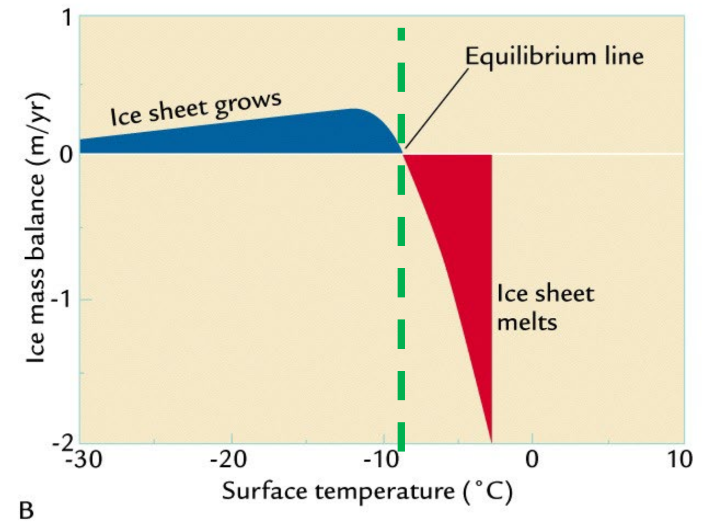
ACCUMULATION, ABLATION, AND NET BALANCE

•**Accumulation (RateACC)**: Accumulation of ice/snow occurs when T°C < 5-10°C. At T°C > 10°C, precipitation falls as rain, while at T°C < -30°C, precipitation is minimal due to low water vapor in frigid air.

•**Ablation**: Rate of ablation (RateABL) increases with rising T°C.

•**Net Mass Balance**: The difference between accumulation and ablation is the **net mass balance**.
The threshold between positive and negative balance is the **equilibrium line**

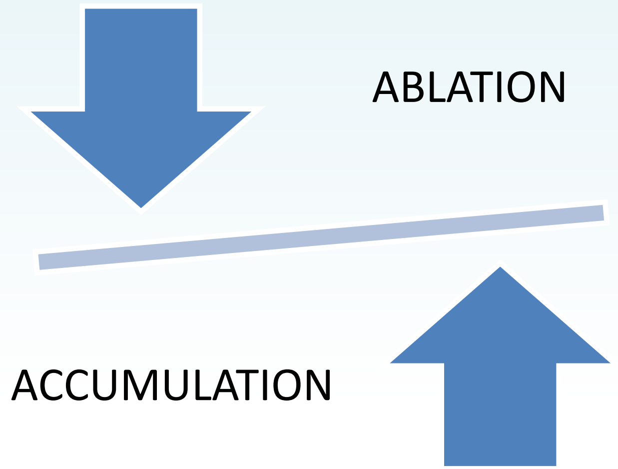




MILANKOVITCH'S THEORY: ORBITAL CONTROL ON THE CAPS -3

If $Rate_{ACC} = Rate_{ABL}$
The ice sheet is in STABLE EQUILIBRIUM

We will instead investigate caps in non-EQUILIBRIUM conditions



Insolation and Ice Expansion
Joseph Alphonse Adhémar (1797–1862) proposed in his 1842 work, *Révolutions de la mer*, a link between changes in insolation and the expansion and retreat of ice caps.

MILANKOVITCH'S THEORY: ORBITAL CONTROL ON THE CAPS -4

Which season controls ice expansion/retreat?

WINTER

Pro:

•Most precipitation occurs in winter. Colder winters (low insolation) support ice and snow accumulation.

Against:

•Ice caps grow at high latitudes, where winter temperatures are consistently low.

SUMMER (Spitaler, Köppen, Wegener; ‘20)

Regardless of winter snowfall, rapid and intense summer ablation can melt it.

Milankovitch’s Theory:

Low insolation leads to cool summers, preserving snow from melting and promoting ice cap growth.

MILANKOVITCH'S THEORY: ORBITAL CONTROL ON ICE SHEET -5

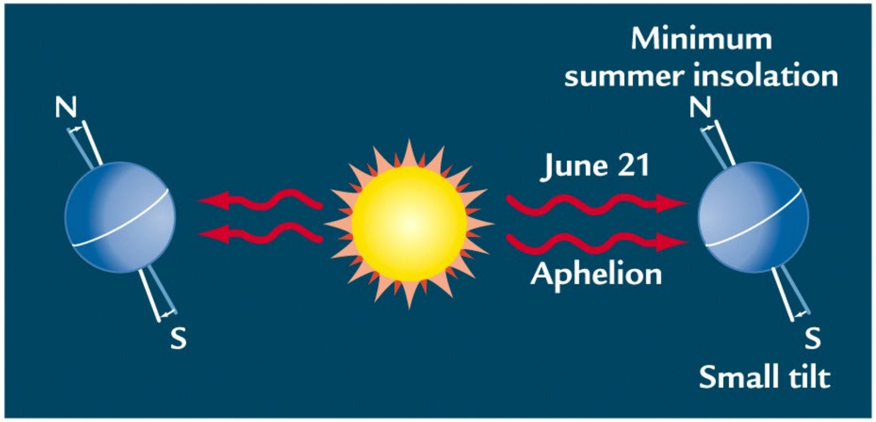
Ice cap growth occurs during summers with low insolation (Fig. A), characterized by:

•Low inclination (low obliquity)

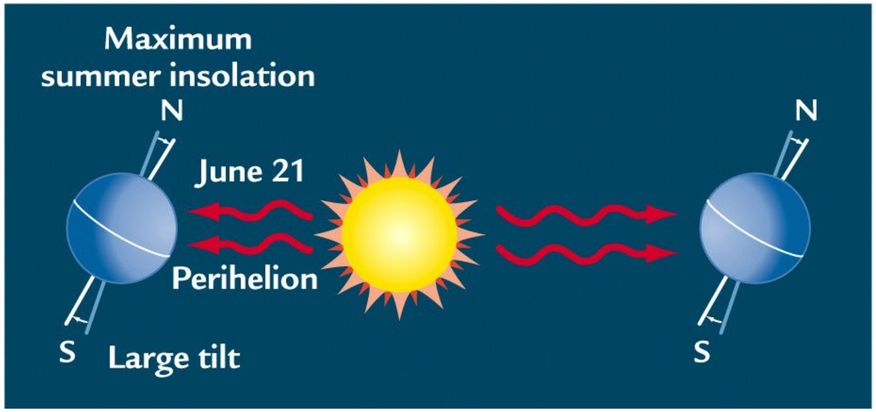
•Summer solstice at aphelion

•Highly eccentric orbit (max eccentricity)

Milankovitch identified 65° N latitude as critical, as snow there first accumulates and then melts. The ice sheet retreats with the opposite orbital configuration (Fig. B).



A Northern hemisphere ice growth



B Northern hemisphere ice decay

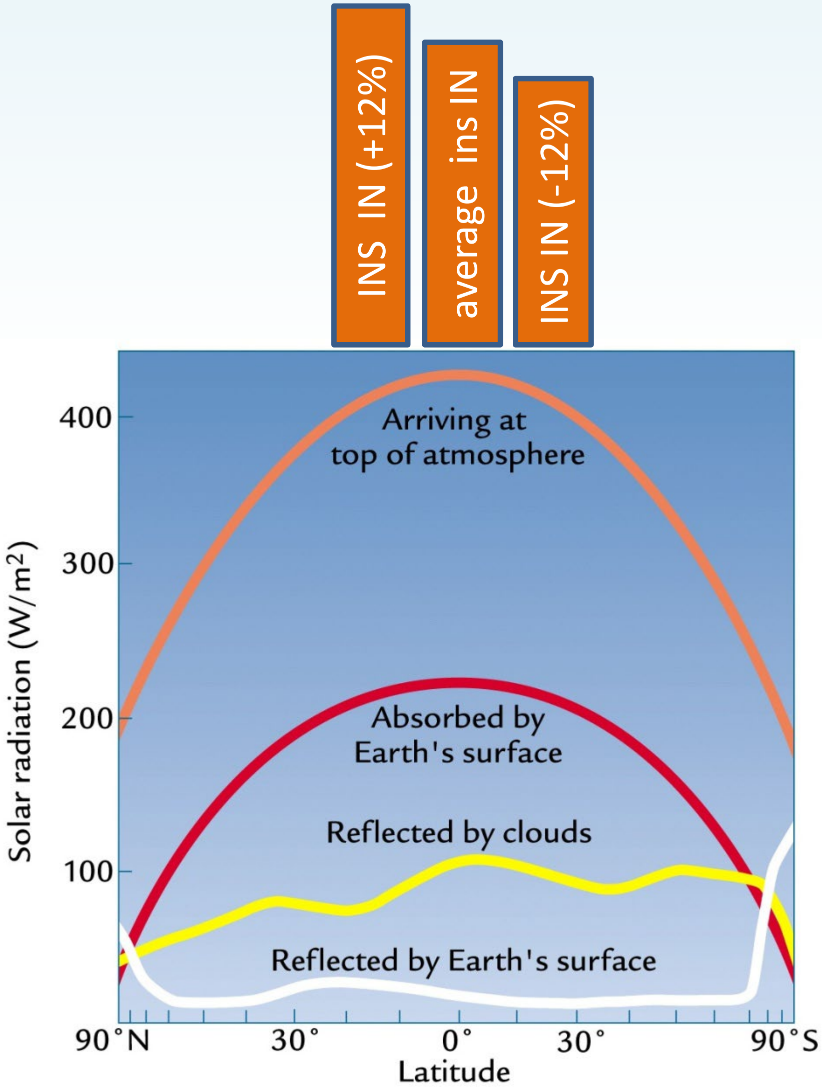
MILANKOVITCH'S THEORY: ORBITAL CONTROL ON ICE SHEET -6

INSOLATION

The insolation reaching Earth's outer atmosphere can vary by up to 12% from the long-term average.

Atmospheric circulation, clouds, and water vapor affect the amount reaching the surface, but we assume:

Insolation at the surface is directly proportional to that entering the atmosphere.



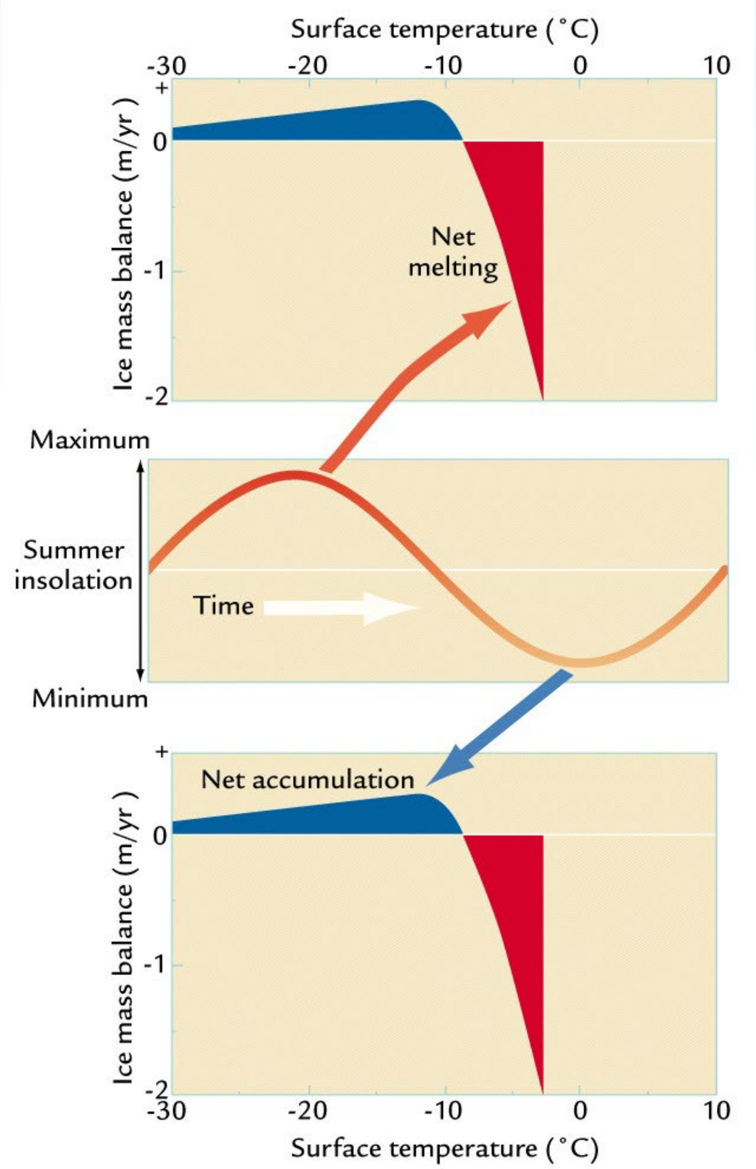
MODELLING ICE-SHEETS

INSOLATION FORCING ON ICE SHEET EVOLUTION

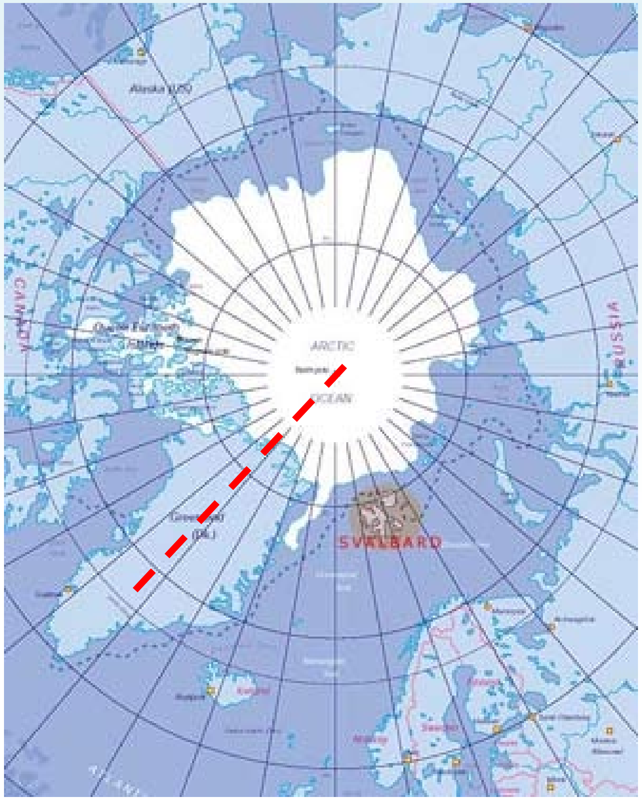
Models of the Arctic ice sheet, based on LGM conditions, assume a single continent (Europe + North America) with an expanding or retreating ice cap.

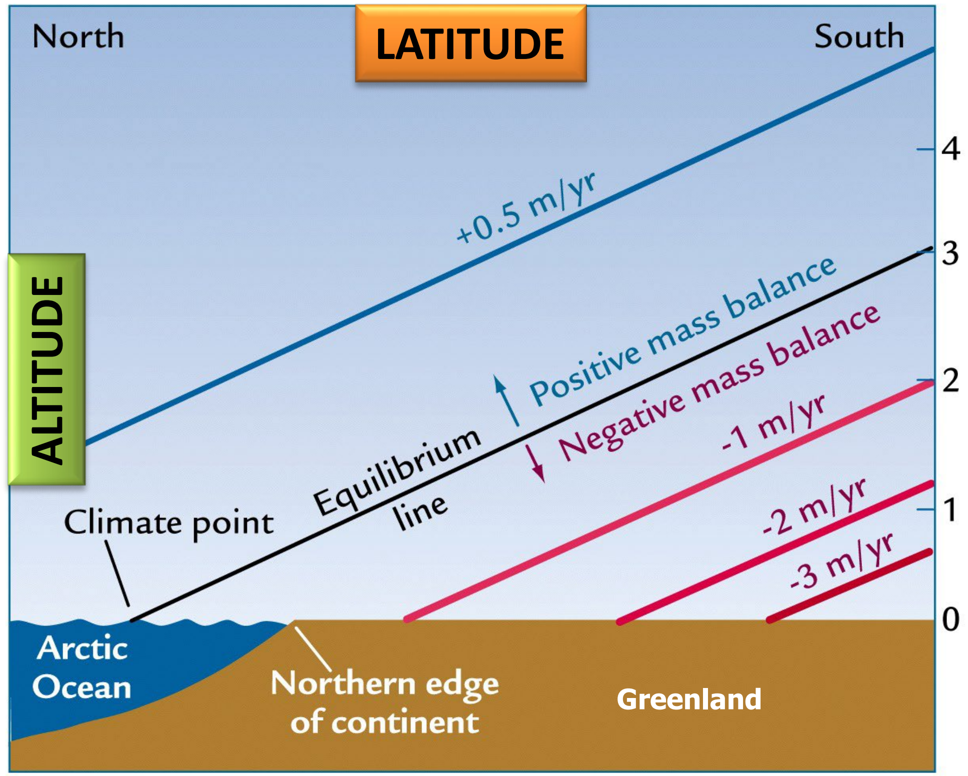
Summer insolation variations alter regional temperatures, impacting ablation rates and the net mass balance.

Expansion of the ice sheet during the LGM



2D MODEL – Greenland





Equilibrium line intercept the Earth's surface at the CLIMATE POINT.

2D Model

allowing this simplified model to simulate long time intervals.

-First dimension is **LATITUDE** (N-S).

-Second dimension is **ALTITUDE** (m).

-Longitude (E-W) variations are not included, allowing this simplified model to simulate long time intervals.

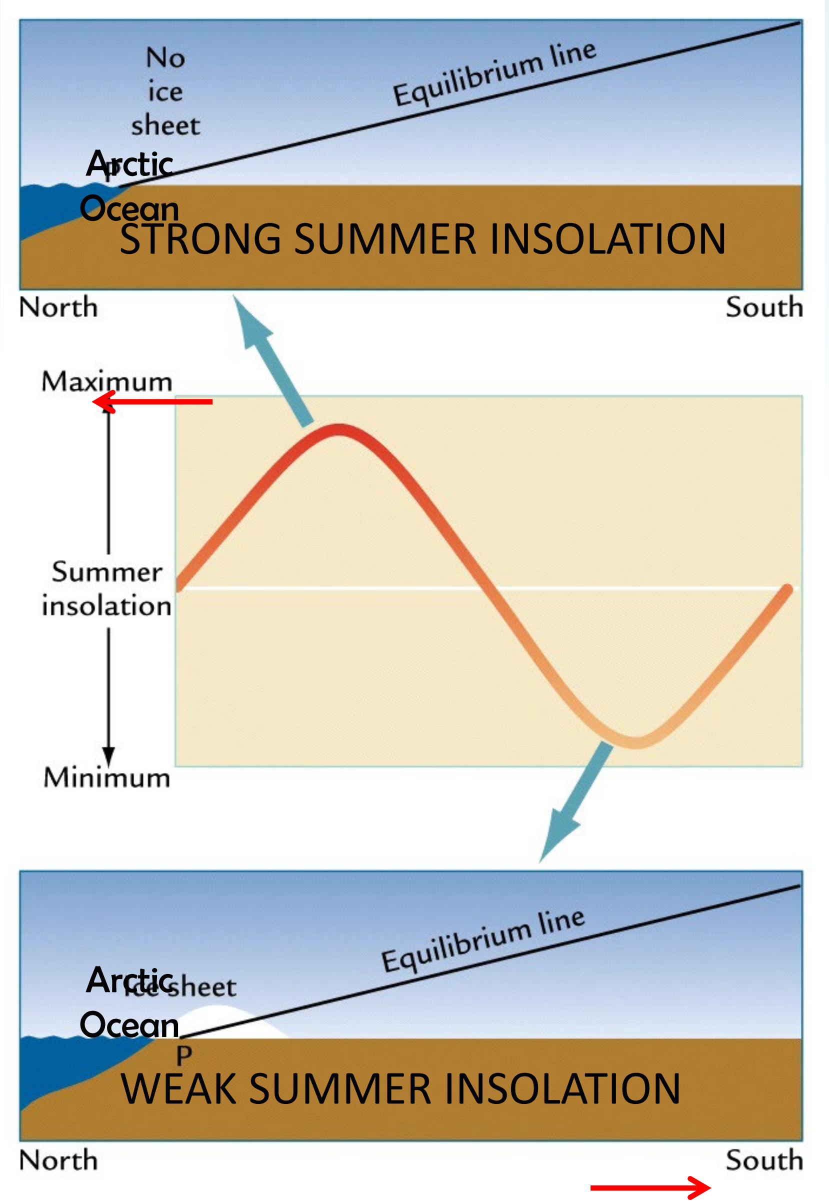
CONTROL OF INSOLATION ON ICE SHEET

These models use summer insolation variations to predict **shifts in the climate point and equilibrium line**.

•**Strong Summer Insolation**: Overall ablation; equilibrium line moves northward.

•**Weak Summer Insolation**: Net accumulation; equilibrium line moves southward.

The latitudinal shift between these extremes is 10-15°.

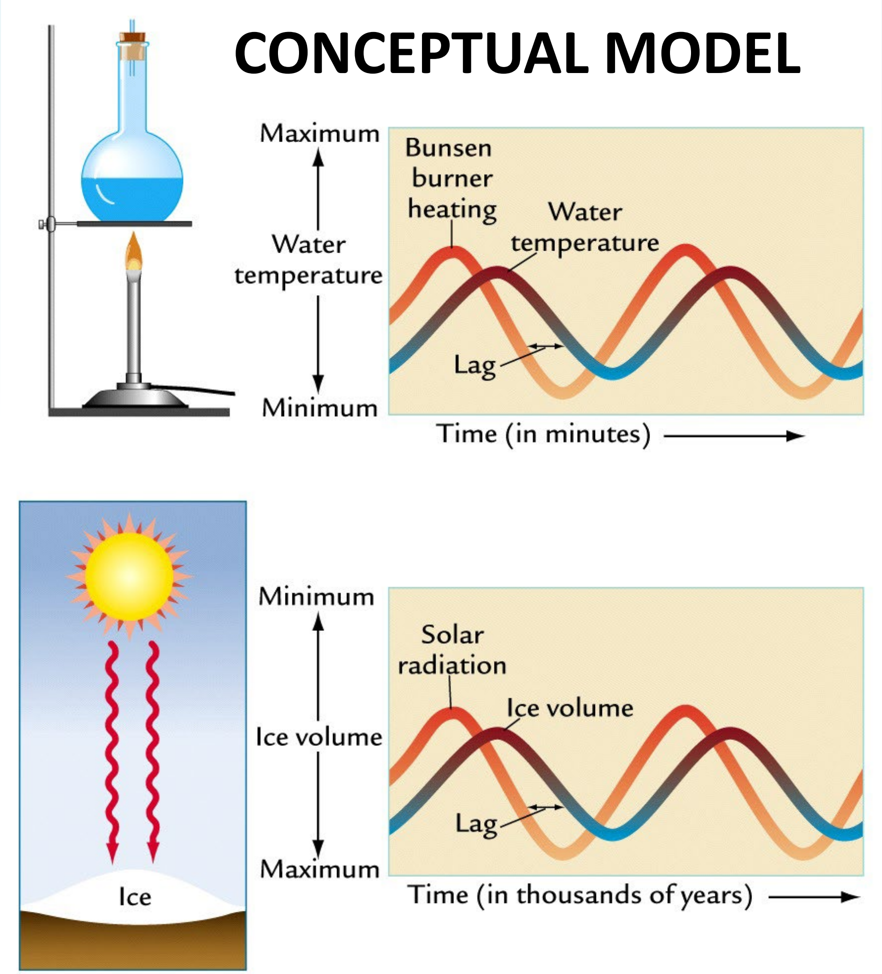


ICE SHEET (CLIMATE RESPONSE) LAG TO SUMMER INSOLATION (FORCING) - 1

Assuming rapid cooling and a 0.3 m/year accumulation rate (ideal conditions), forming a 3 km thick ice cap would take at least 10 kyr.

Ice Caps / Insolation Lag (Imbrie et al.)
Snow accumulation lags behind insolation changes.

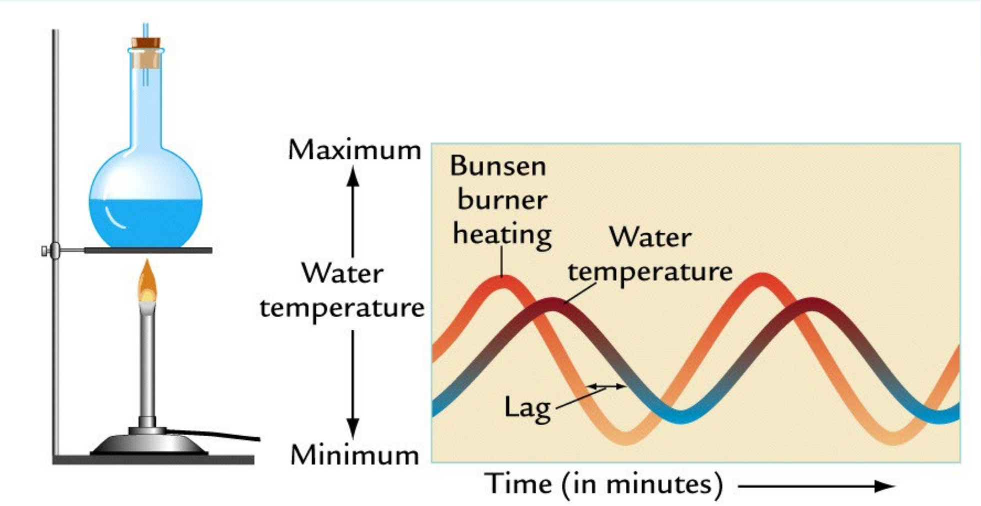
A conceptual model compares the solar radiation + ice volume system to the Bunsen system + H_2O (high thermal capacity), showing a delay in response to forcing.



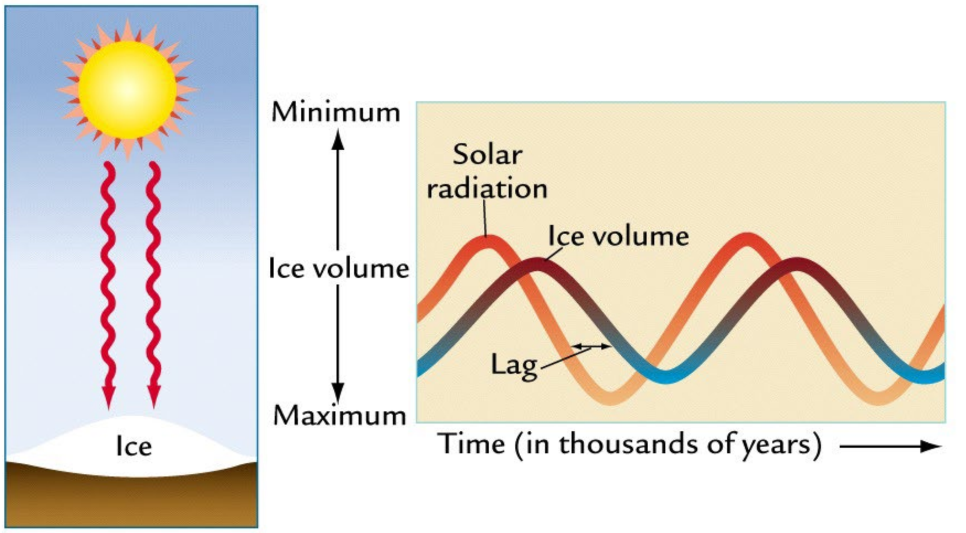
Bunsen= Insolation
Water Temperature= Ice Volume

ICE SHEET (CLIMATE RESPONSE) LAG TO SUMMER INSOLATION (FORCING) - 2

When **summer insolation decreases**, ice begins to accumulate, with the highest accumulation rate occurring at minimum insolation. Maximum ice accumulation, however, lags behind the summer insolation minimum.

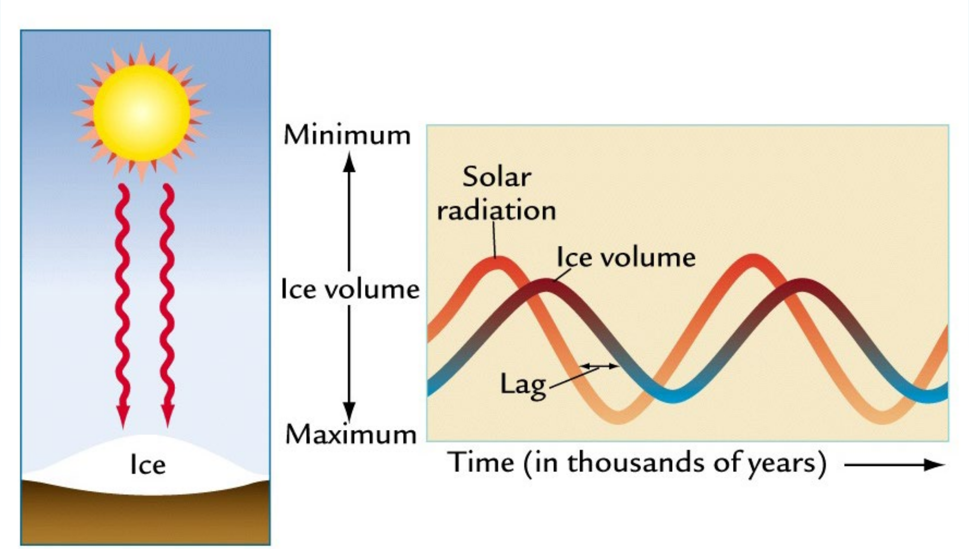


As **summer insolation begins to increase**, the ice cap continues to grow since insolation remains low. The ice cap reaches its minimum size at the onset of net ablation, continuing in this cycle.



ICE SHEET (CLIMATE RESPONSE) LAG TO SUMMER INSOLATION (FORCING) - 3

The delay between changes in summer insolation and ice volume is called phase lag, with ice volume lagging by ¼ of a cycle.



The relationship between summer insolation and ice volume can be expressed by this equation:

$$\frac{d(I)}{d(t)} = \frac{1}{T}\,(S - I)$$

$\frac{d(I)}{d(t)}$ = *tasso di variazione del volume dei ghiacci per unità di tempo(t)*

I = *ice volume*

T = *ice cap response time (Kyr)*

S = *summer insolation*

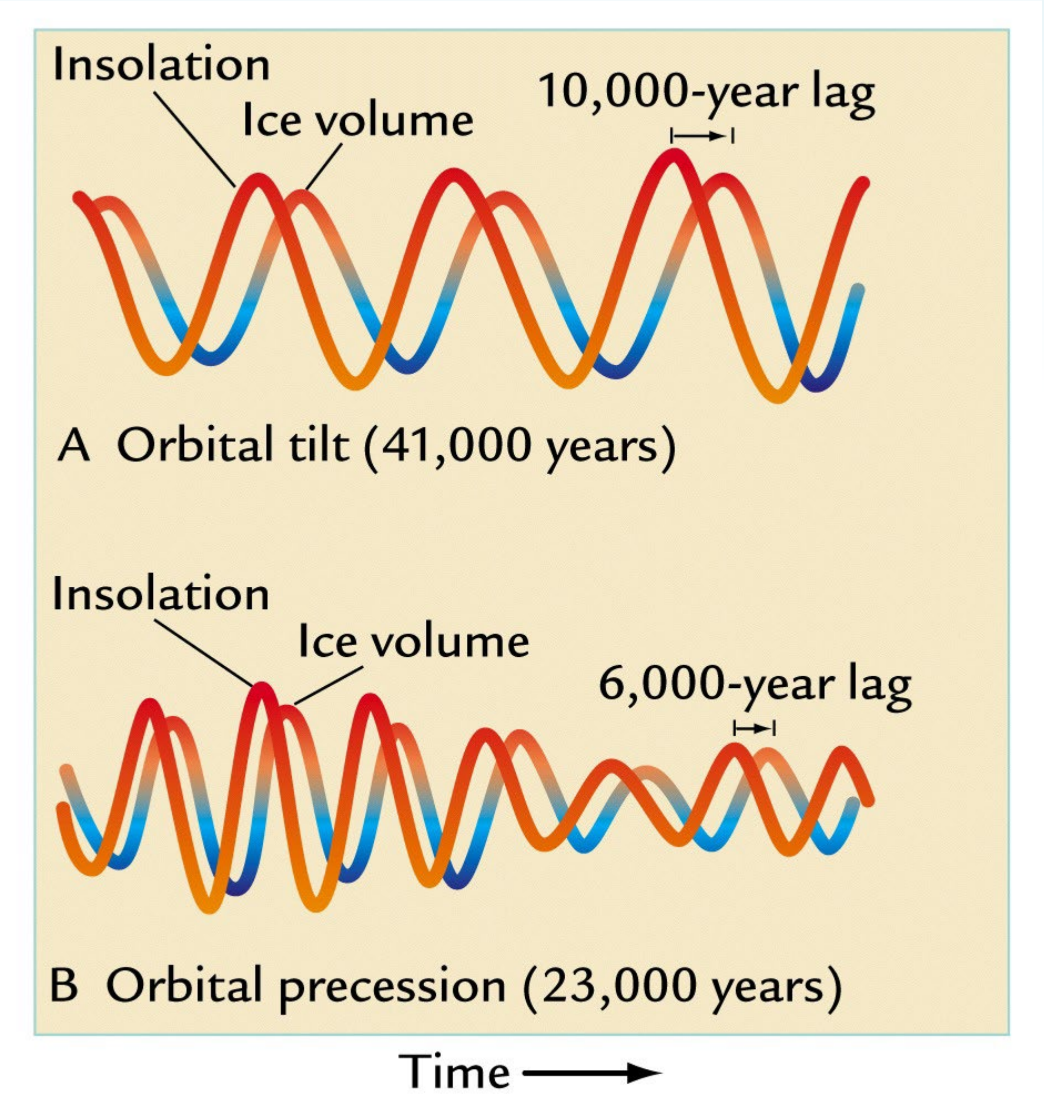
S-I = *phase lag between forcing and climate response*

ICE SHEET (CLIMATE RESPONSE) LAG TO SUMMER INSOLATION (FORCING) - 4

This model can also distinguish ice volume changes due to obliquity from those due to precession:

Obliquity cycles: Response lags by ¼ cycle (~10 kyr).

Precession cycles: Response lags by ¼ cycle (~6 kyr).



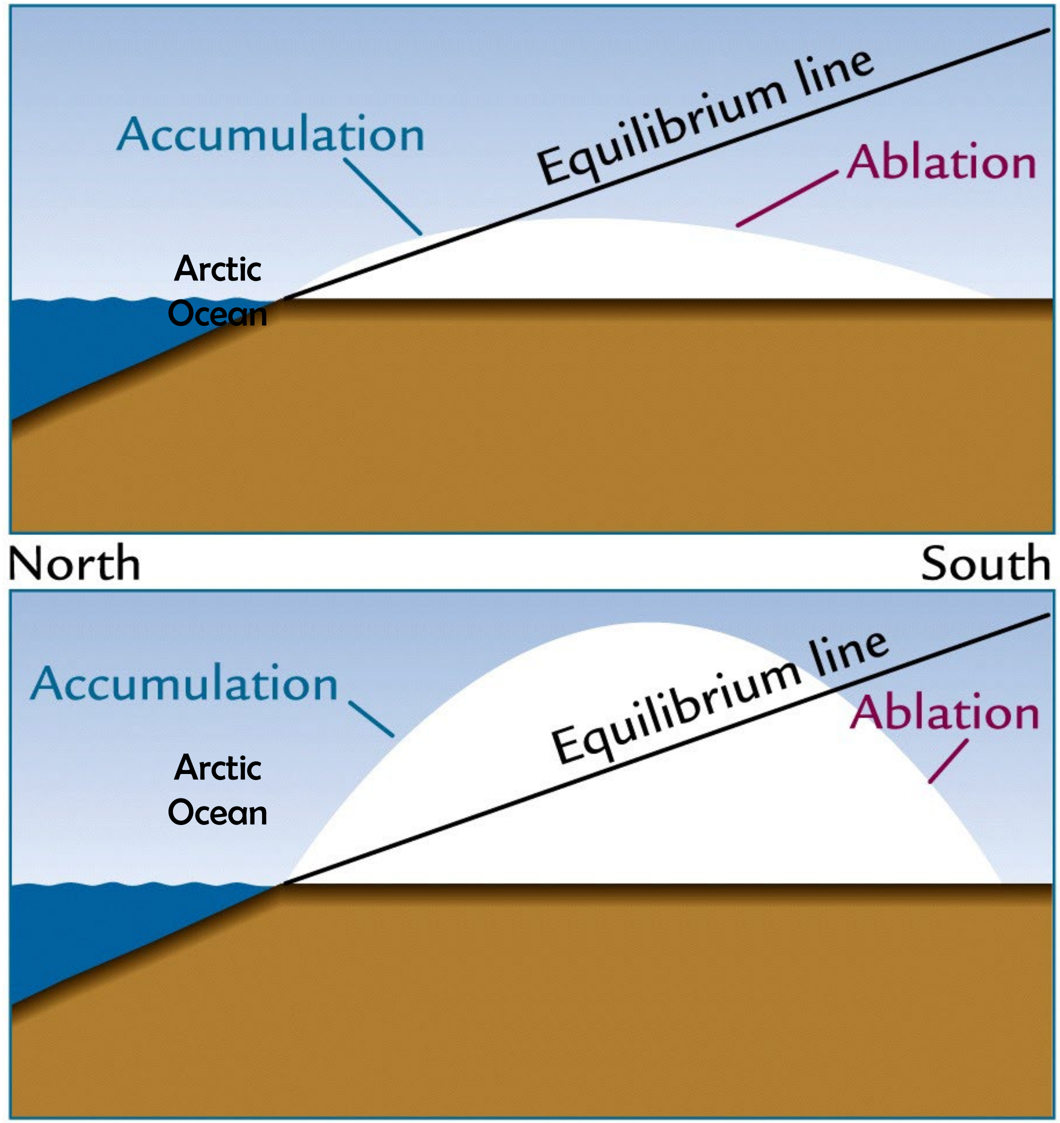
ICE ELEVATION FEEDBACK

THE ICE SHEET SUSTAINS ITSELF

As the ice cap thickens (up to 2-3 km), its surface attains higher altitudes, resulting in colder temperatures.

In a regime of net accumulation, the colder temperatures facilitate increased accumulation.

In essence, as the ice cap starts to expand, it actively contributes to the increase of the net balance—essentially, it sustains itself.

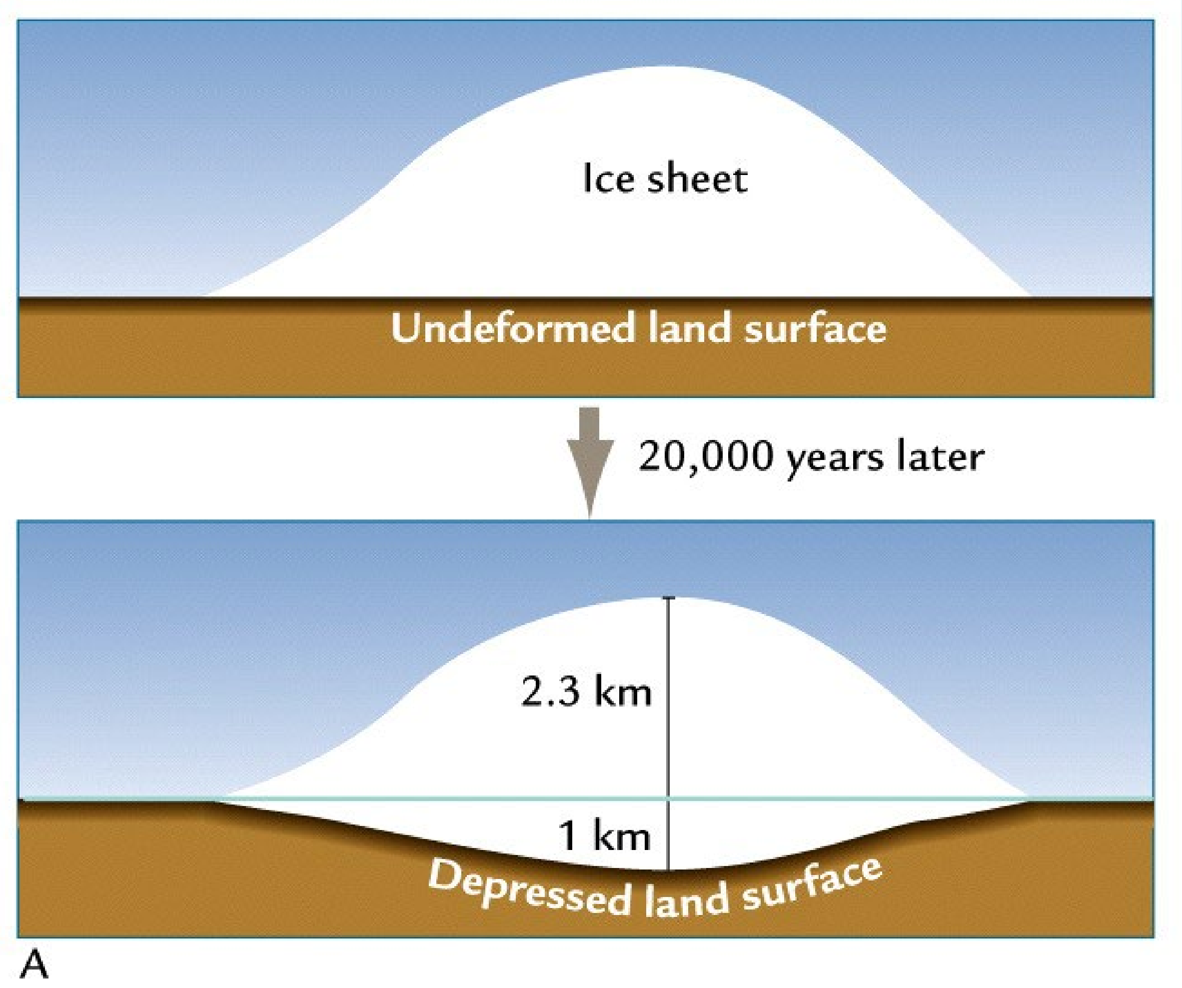


BEDROCK FEEDBACK: SUBSIDENCE AND REBOUND -1

As the ice cap expands, it adds an isostatic load on the bedrock.

With ice density at ~1 g/cm³ and bedrock at ~3.3 g/cm³, a 3km thick ice cap depresses bedrock by about 1km.

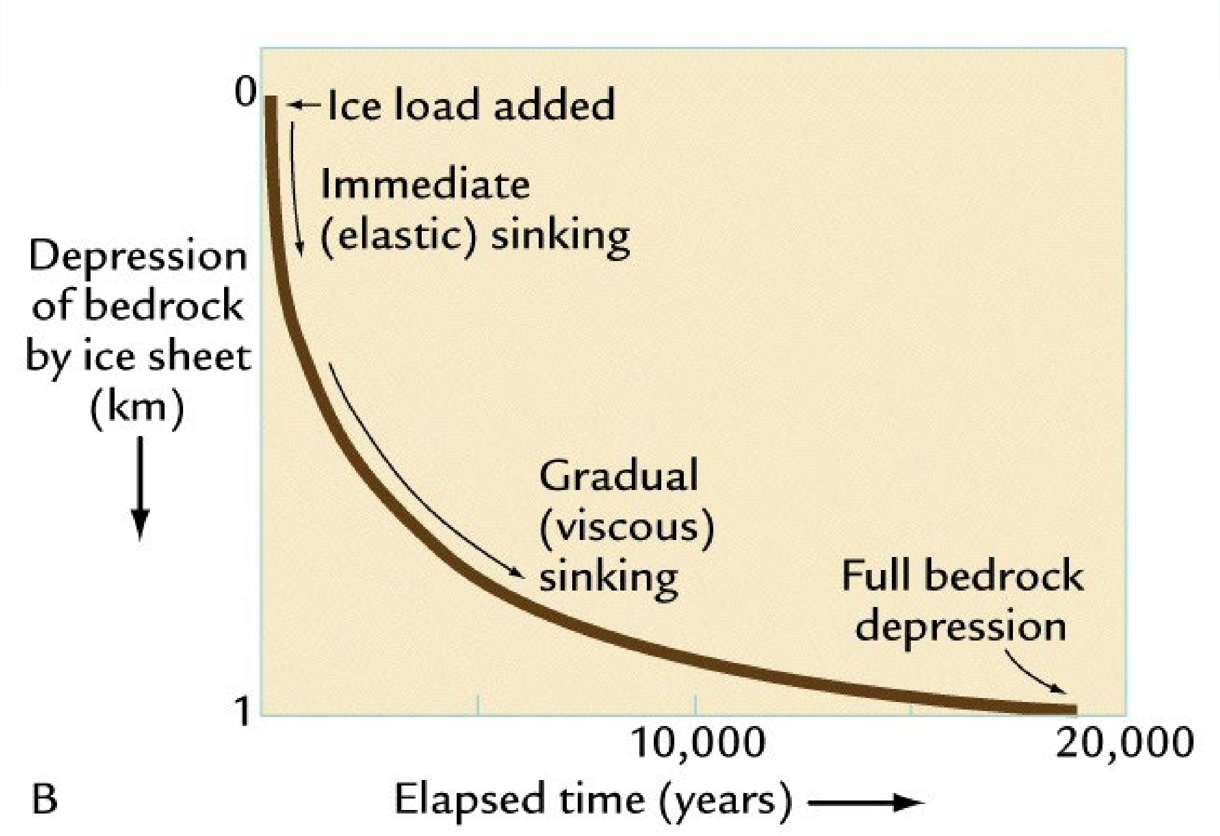
This altitude difference raises temperatures by roughly 6.5°C, promoting ice melting.



BEDROCK FEEDBACK: SUBSIDENCE AND REBOUND -2

This deformation occurs in two stages:

1. **Immediate elastic deformation (30%)**
2. **Gradual viscous deformation**



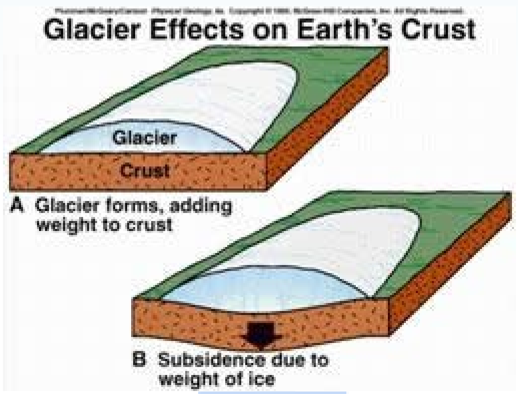
BEDROCK FEEDBACK:SUBSIDENCE AND REBOUND -3

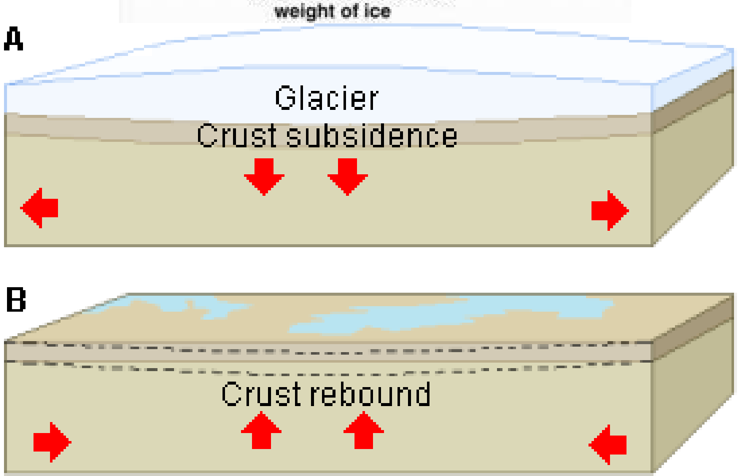
Isostatic Load Effects of Ice Sheets:

•**Subsidence** during glacial phases

•**Uplift** during post-glacial phases (e.g., Scandinavia)

A)





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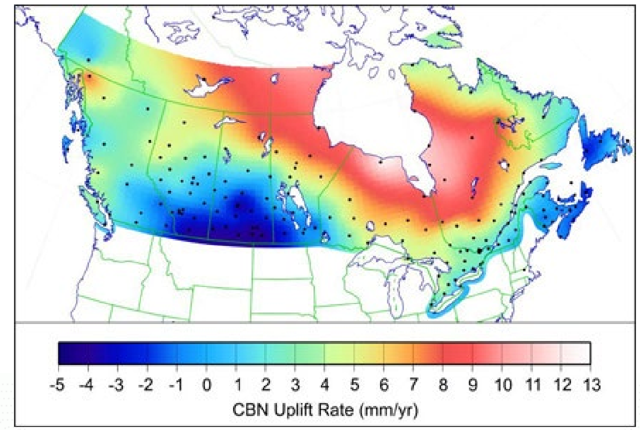
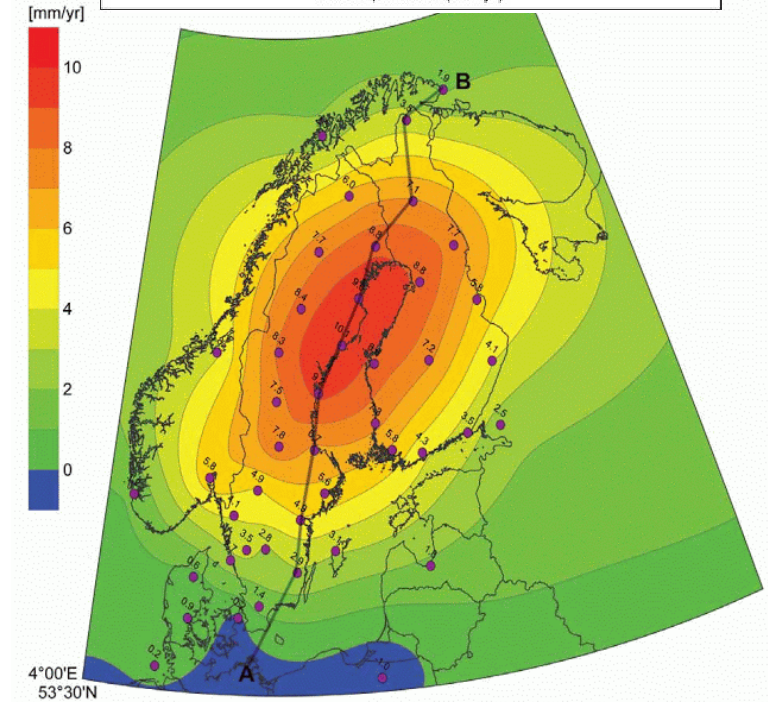




BEDROCK FEEDBACK

ICE CAP GROWS

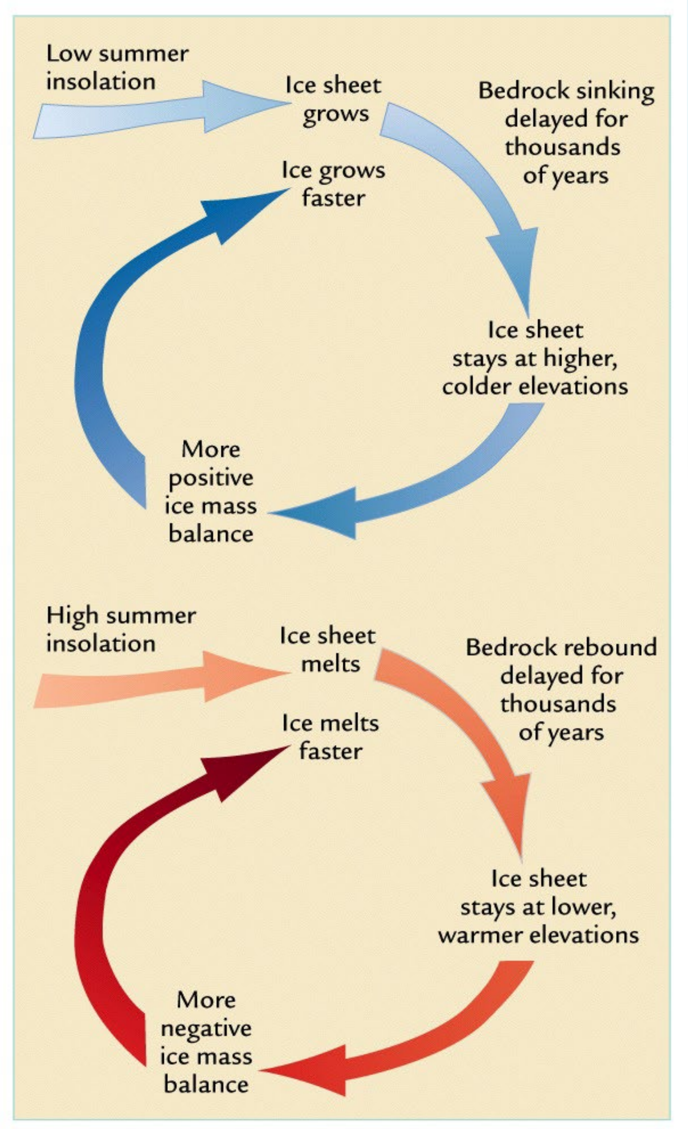
Immediate elastic sinking → initial melting.

Viscous (slow) sinking + ice sheet growth
→ the ice sheet stays at high altitudes
→ stimulates growth.

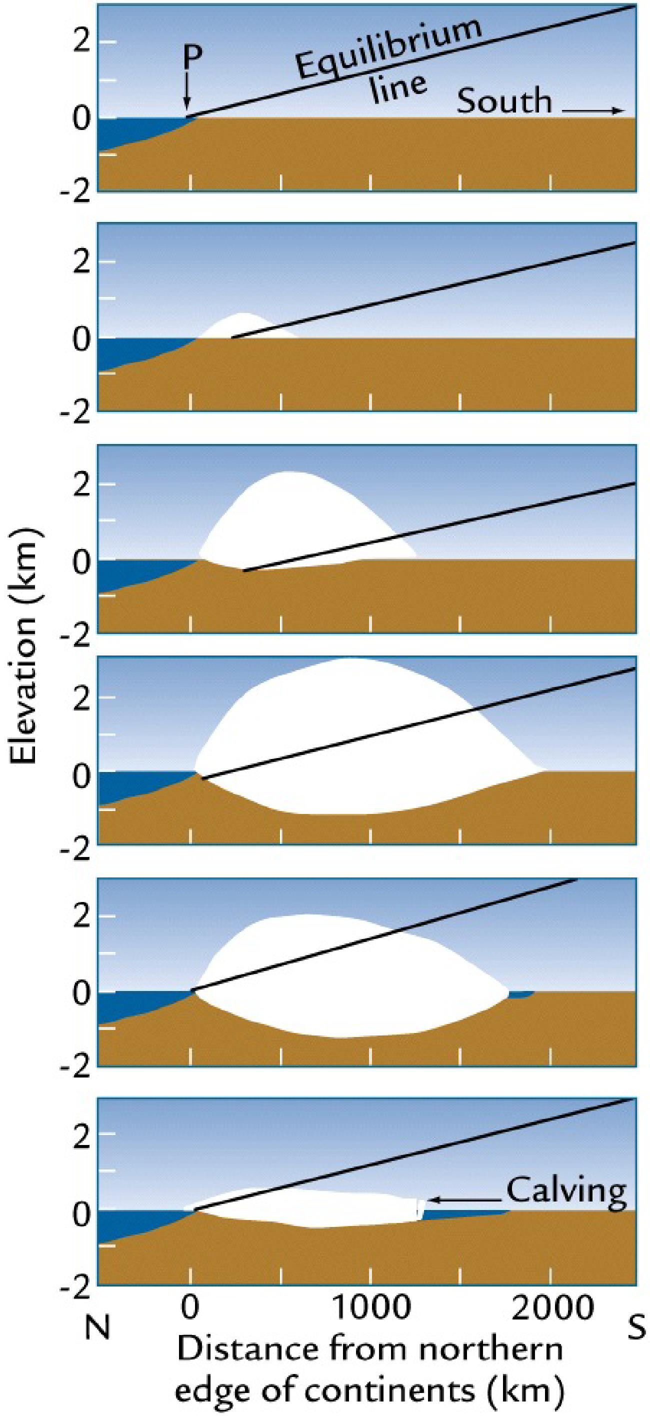
ICE CAP DECREASES

Immediate elastic uplift → initial growth.

Viscous (slow) uplift + ice cap melting
→ moves at low altitudes
→ favors the melting.



RELATIONSHIP BETWEEN INSOLATION, ICE VOLUME AND BEDROCK FEEDBACK



A No ice sheet (interglacial)

B Insolation drops, equilibrium line shifts south, ice sheet starts to grow

C Insolation at a minimum, ice sheet grows rapidly, ice depresses bedrock

D Insolation rises, equilibrium line moves north, ice sheet at maximum size, bedrock depression increases

E Insolation at a maximum, equilibrium line far to north, ice melts rapidly, bedrock starts to rise

F Insolation starts to drop, last ice remnants melt, bedrock rises rapidly

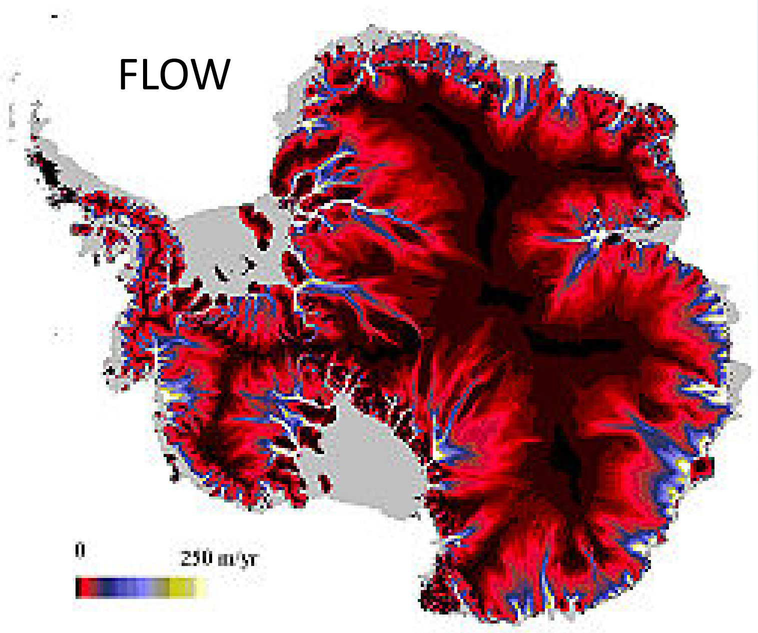
ICE FLOW, SLIPPING AND CALVING

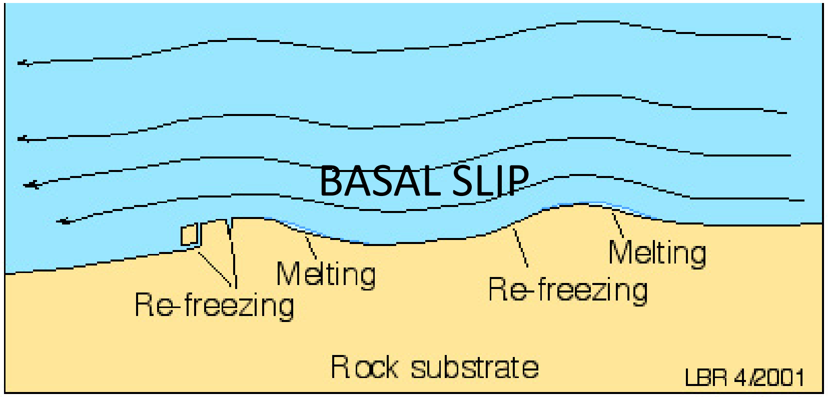
In ice caps, ice movement occurs through several mechanisms, some predictable, others harder to model:

•**Flow**: Ice flows from cold, high net accumulation areas to warm, low net ablation areas, modeled as slow diffusion from high to low regions.

•**Basal Slip**: Meltwater at the ice sheet base creates "lubricated" layers, allowing the ice to slide.

•**Iceberg Calving**: Ice detaches at the edges of the ice cap.





HISTORY OF THE ARCTIC ICE SHEET

On the Continents

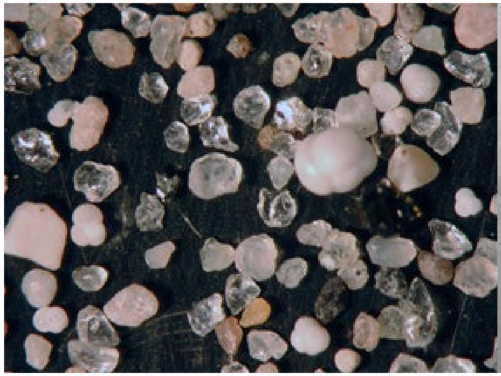
Ice erodes underlying sediments, forming moraines that may be erased in later glacial phases.

Morainic cord on Mer de Glace (FR)

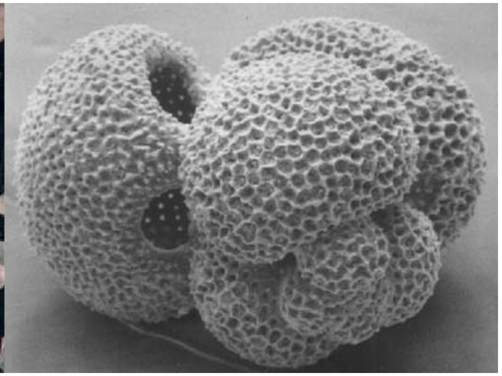
In the Oceans

Continuous sediment sequences provide key indicators of glaciations:

- Ice-Rafted Detritus (IRD)
- $\delta^{18}O$ records from foraminifera



Ice-Rafted Detrius (IRD)



G. ruber

Decoding Oxygen Isotopes: Insights into Temperature, Ice Volume, and Insolation

Emiliani (1950-1960)

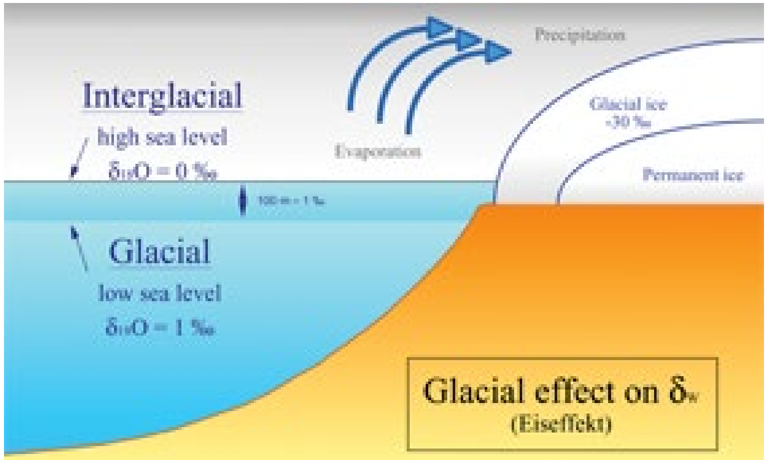
$\delta^{18}O$ records over the past hundreds of thousands of years serve as a temperature proxy.

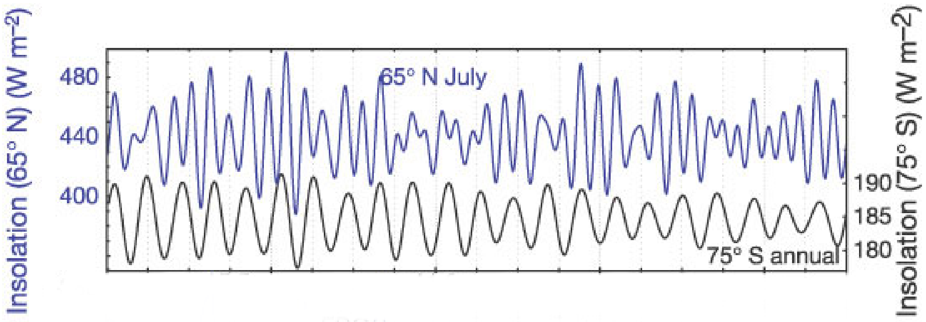
Shackleton (1967)

$\delta^{18}O$ reflects ice volume changes, influenced by temperature.

Hays, Imbrie, and Shackleton (1976)

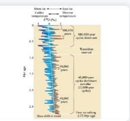
Proposed that $\delta^{18}O$ is linked to orbital insolation variations, showing clear orbital cycles and a delay between insolation and $\delta^{18}O$ response.





Which trend(s) can you recognize in the oxygen isotope curve of the last 2.7 Myr?

Exit



Which trend/trends can you

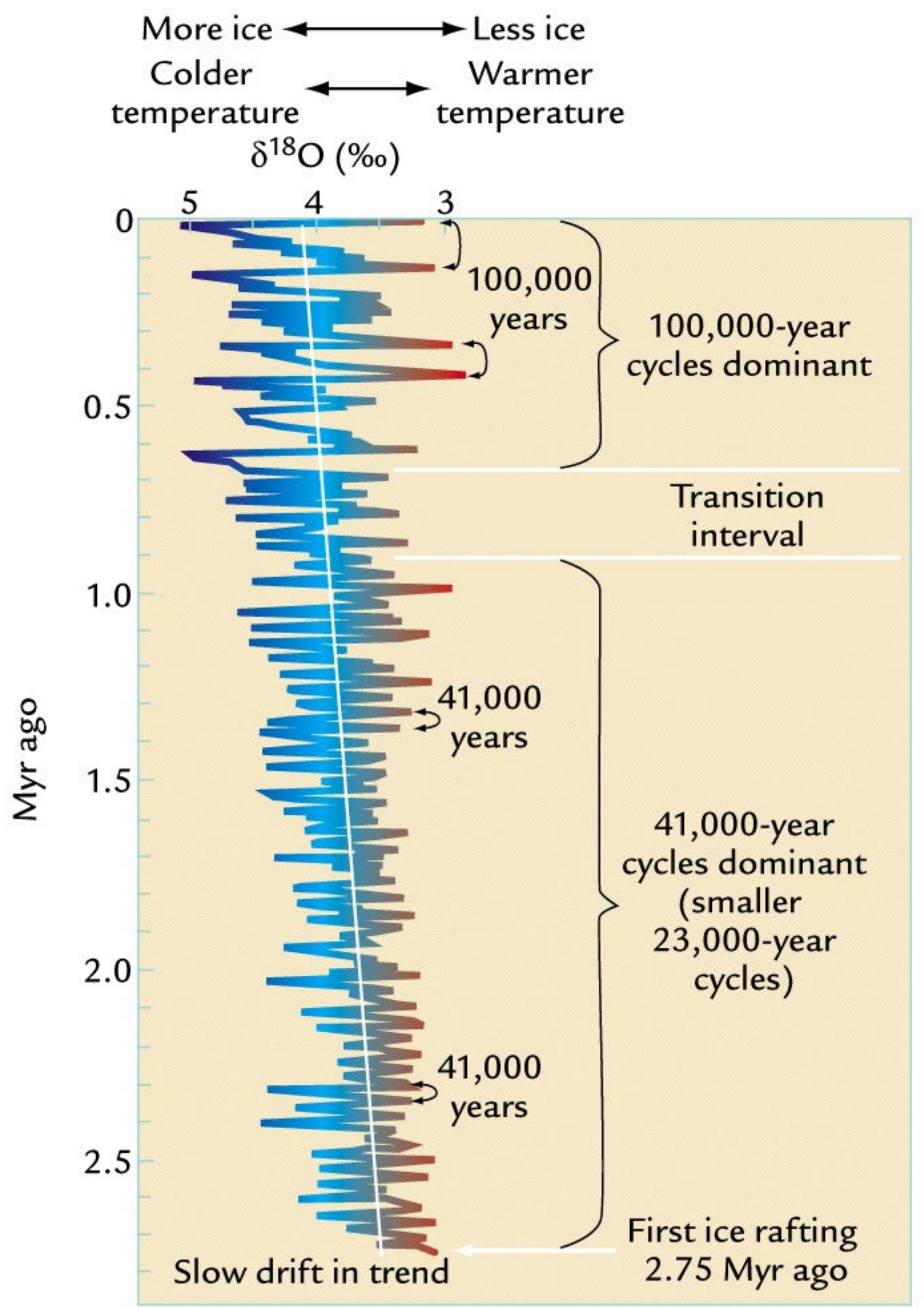
1 long-term 0% 0

2 short-term 0% 0

3 both 0% 0

4 none 0% 0

https://app.wooclap.com/events/PCCM24/0



More ice
Less ice
Colder temperature
Warmer temperature
δ18O (‰)
5
4
3
0
0.5
1.0
1.5
2.0
2.5
Myr ago
100,000 years
100,000-year cycles dominant
Transition interval
41,000 years
41,000-year cycles dominant (smaller 23,000-year cycles)
41,000 years
First ice rafting 2.75 Myr ago
Slow drift in trend

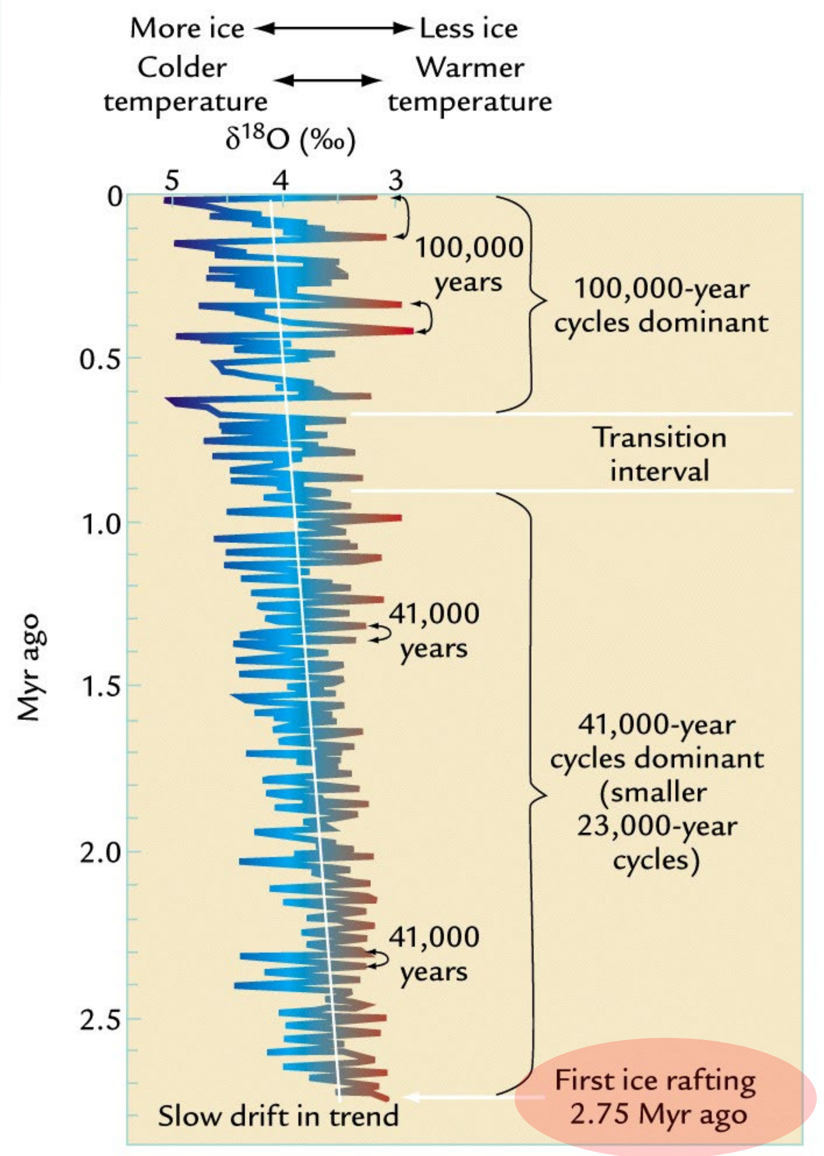
THE LAST 2.75 MILLION YEARS

Raymo (1994)
Raymo's record of the Arctic ice sheet, spanning the last 2.75 Ma, shows two main trends:

1. **A gradual increase in δ^{18}O**
2. **Cyclical fluctuations**

Before 2.75 Ma, δ^{18}O values were lower, and Ice-Rafted Detritus (IRD) was absent. In the past 2.75 million years, IRD appeared, extending to lower latitudes during glaciations.

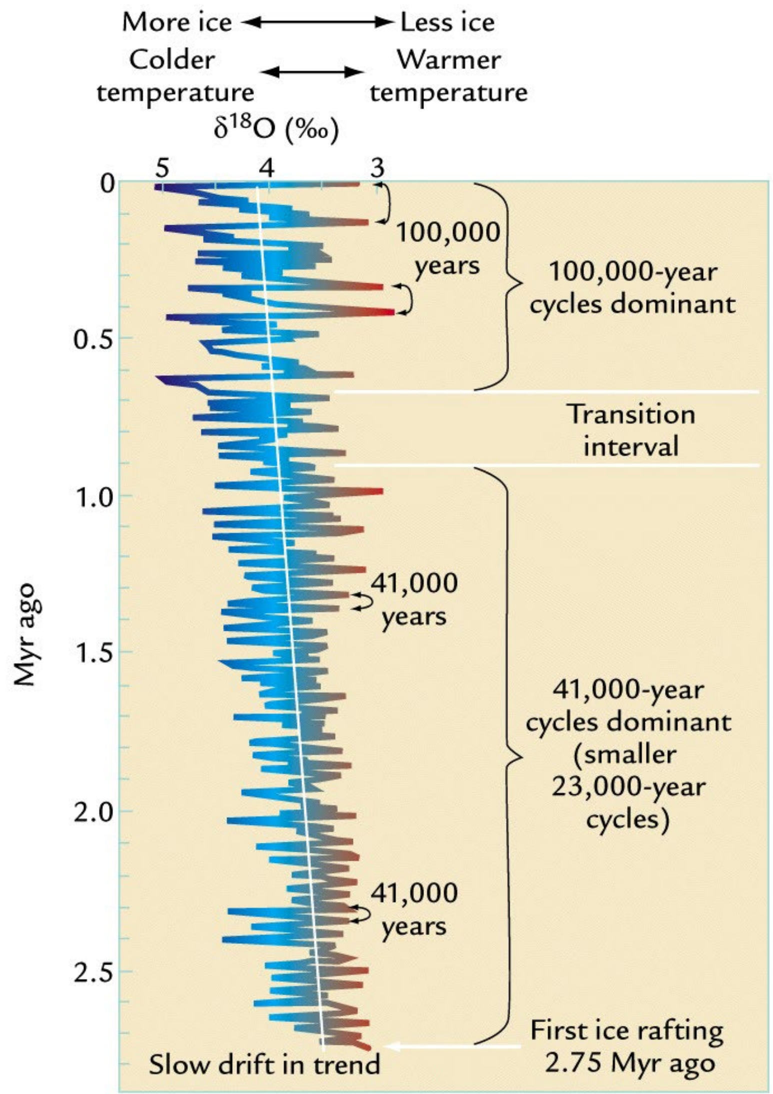
•**2.75 to 0.9 Ma**: 41 kyr cycles (about 50 glaciations), with long-term cooling.
•**0.9 Ma to present**: 100 kyr cycles with rapid deglaciations (terminations).

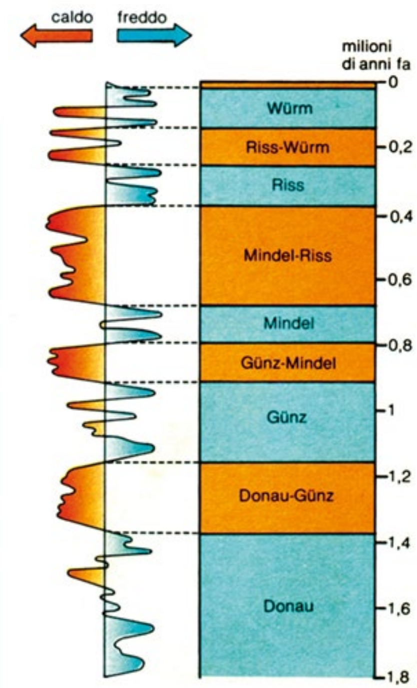


MILANKOVITCH AND HIS INTUITION

Milankovitch (1879-1958) developed a theory explaining the cyclic pattern of glacial and interglacial periods, based on limited continental data suggesting around 4-5 glaciations.

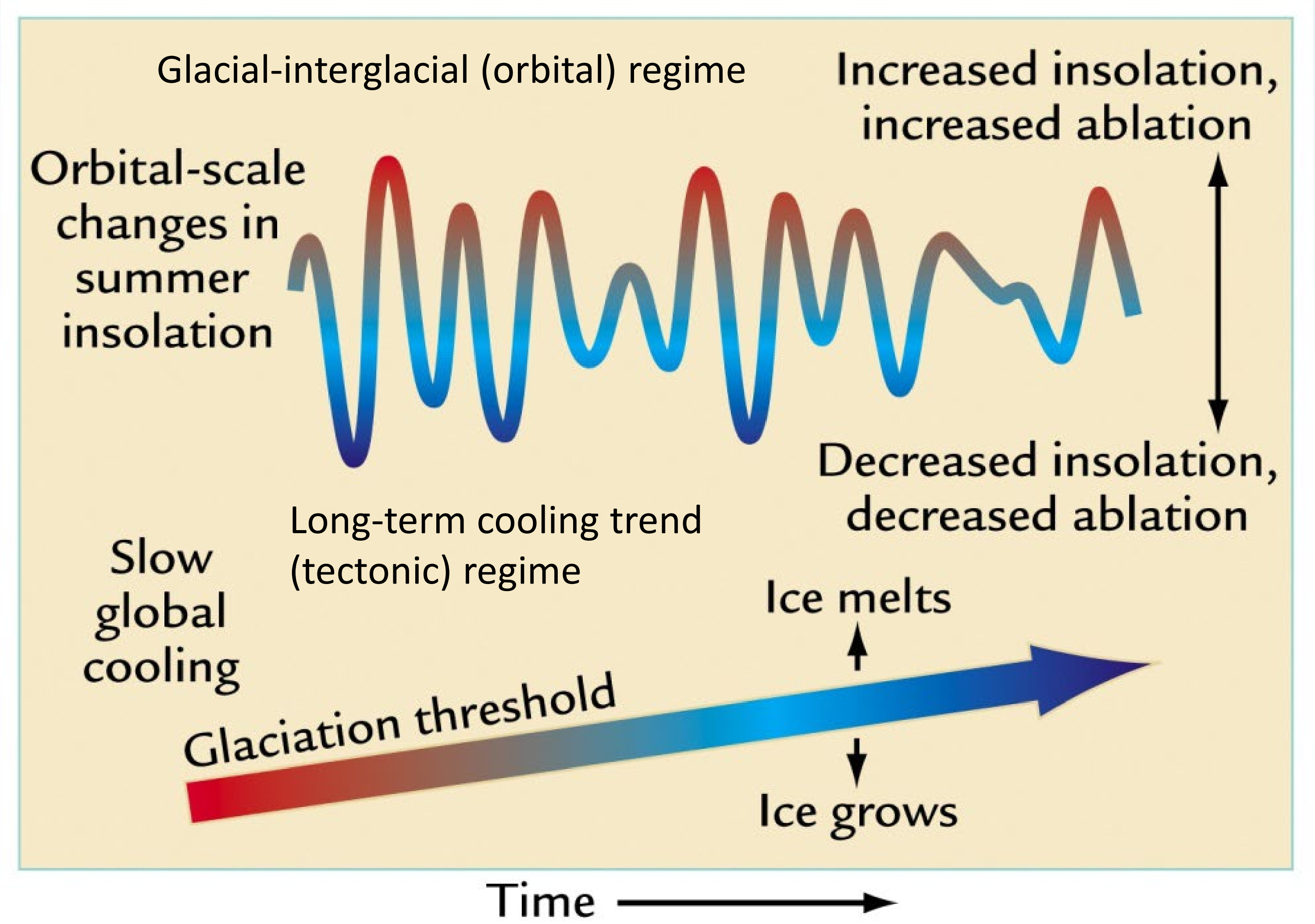
MARINE (50) VS CONTINENTAL (5)





Wurm: 15-70 kyr
Riss. 125-200 kyr
Mindel: 240-455 kyr
Gunz: 620-685 kyr
Donau: 1500-1800 kyr

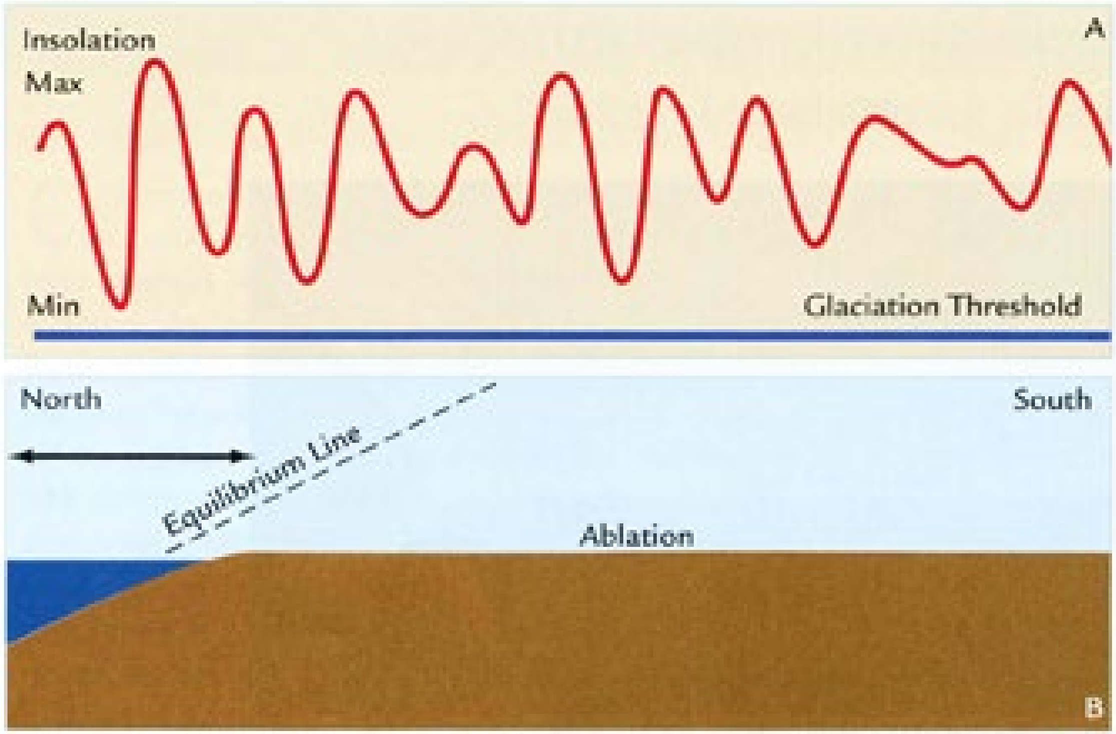
CONTROLLING FACTORS FOR THE DEVELOPMENT OF THE ARCTIC ICE SHEETS



CONCEPTUAL MODEL OF THE EVOLUTION OF THE ICE CAPS-1

PRE-GLACIATION PHASE

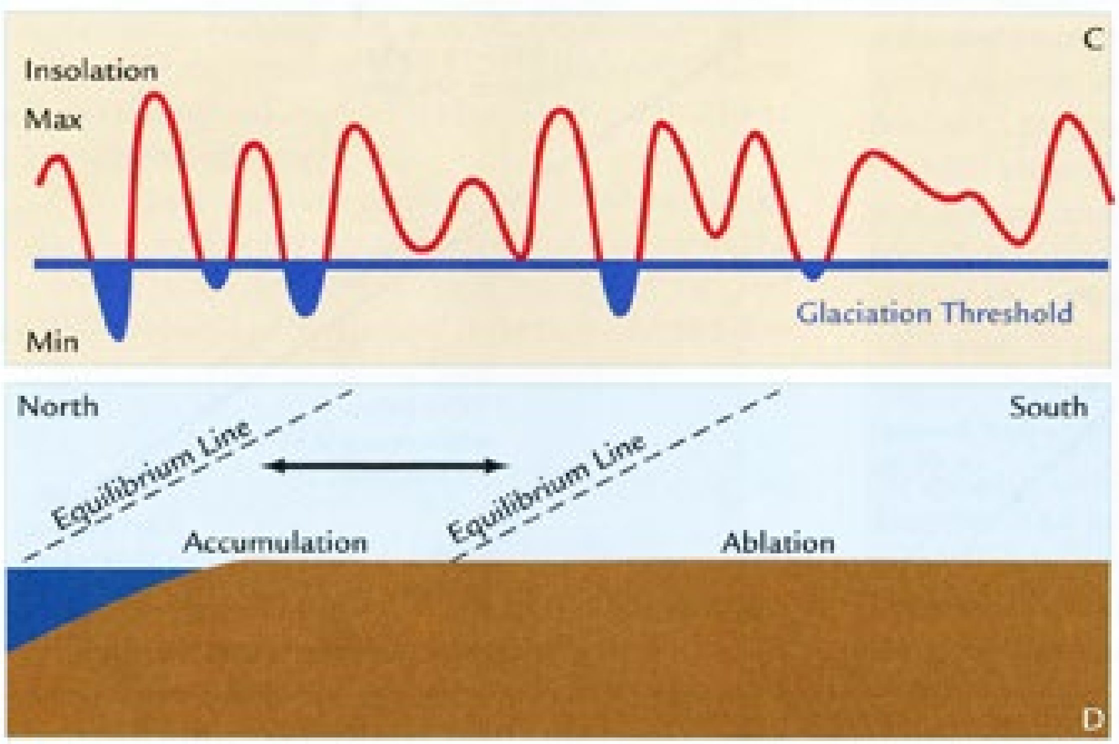
Conditions for ice cap formation in the Northern Hemisphere were absent, even during low summer insolation.



CONCEPTUAL MODEL OF THE EVOLUTION OF THE ICE CAPS-2

SMALL GLACIATION PHASE (2.75-0.9 MA)

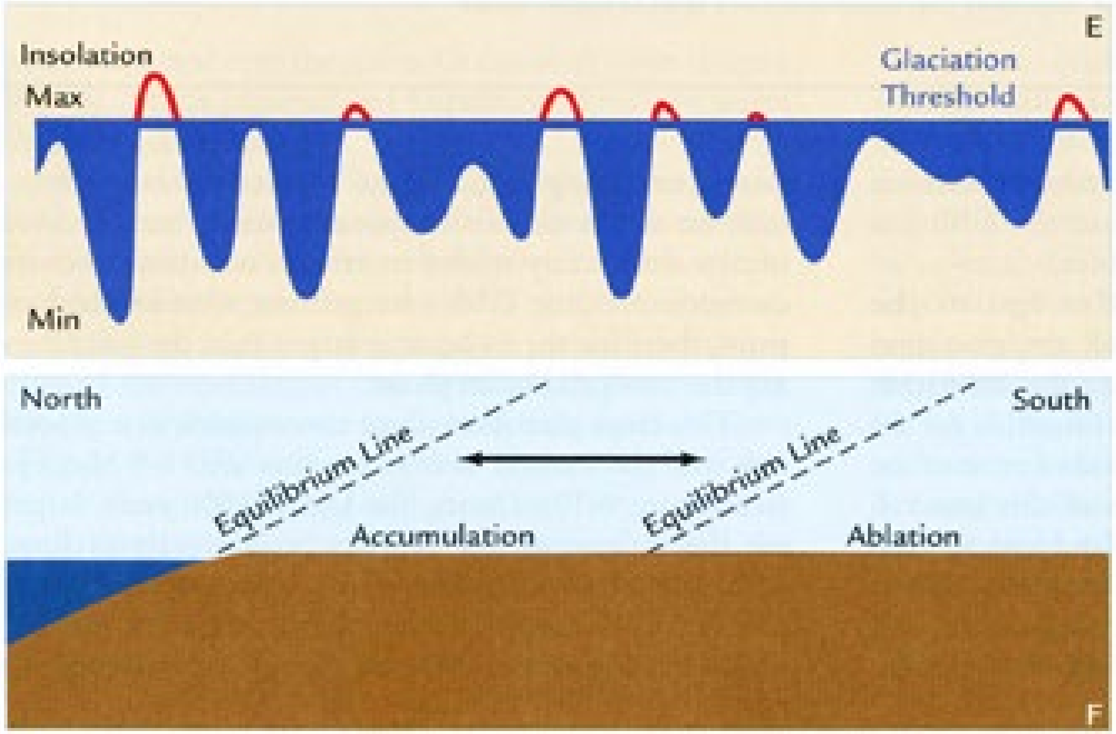
Persistent global cooling shifted the equilibrium line. During low summer insolation, ice caps expanded but remained limited in size as insolation started to increase, causing melting.



CONCEPTUAL MODEL OF THE EVOLUTION OF THE ICE CAPS-3

LARGE GLACIATION PHASE (0.9 MA-PRESENT)

Continued cooling further shifted the equilibrium line, favoring larger ice cap growth, with the climate point remaining on land masses.

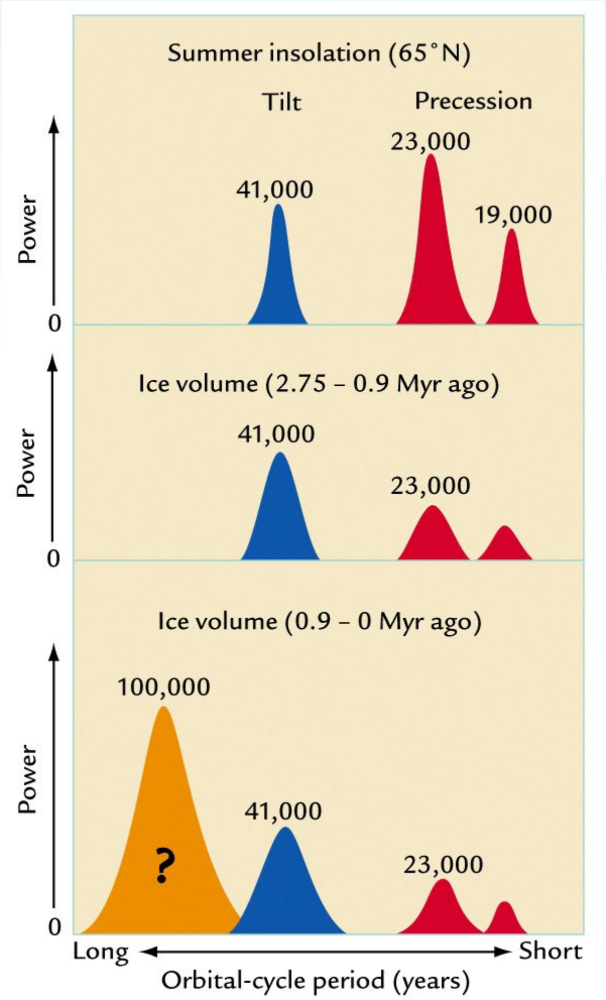


CONCEPTUAL MODEL OF THE EVOLUTION OF THE ICE CAPS-4

Milankovitch's theory explains many aspects of the glacial regime, but ...

The dominance of the 41kyr cycles in the oscillations observed between 2.75 and 0.9 Ma.

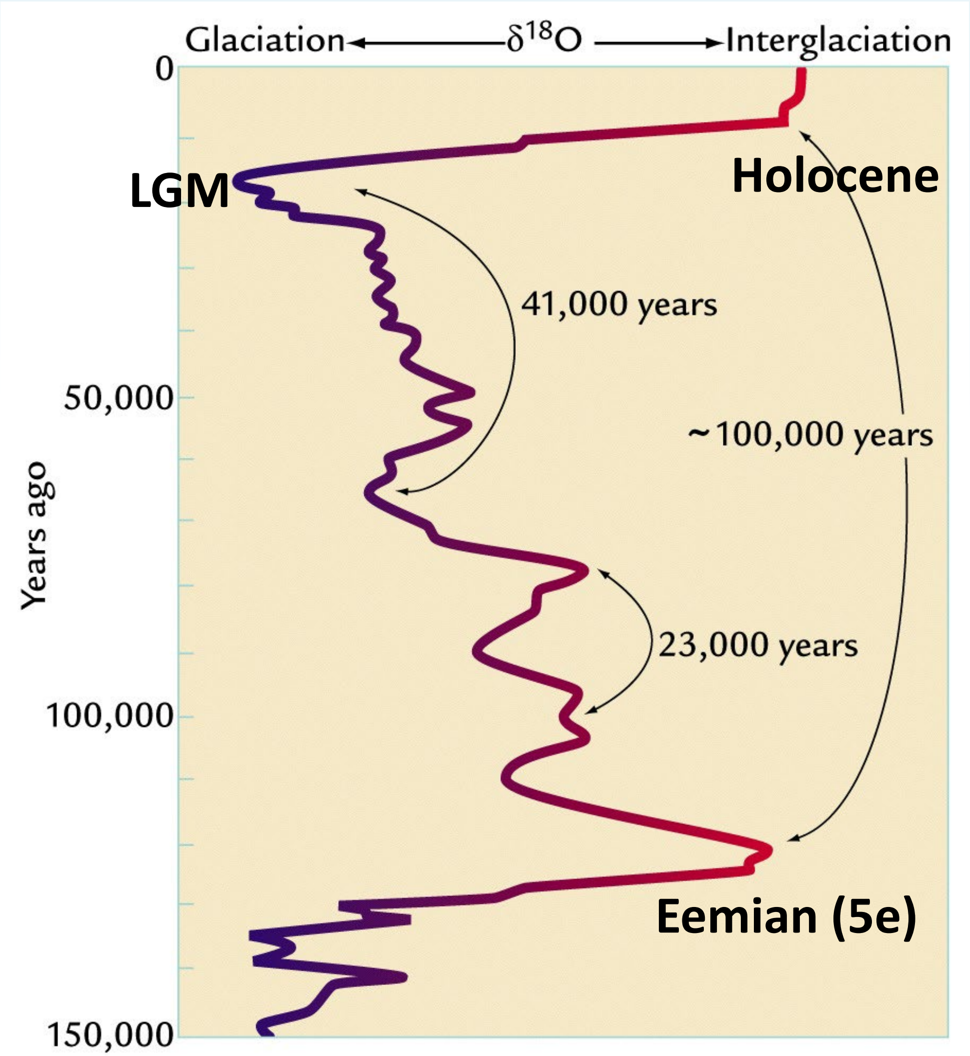
The dominance of 100kyr cycles in the last 0.9 Myr.



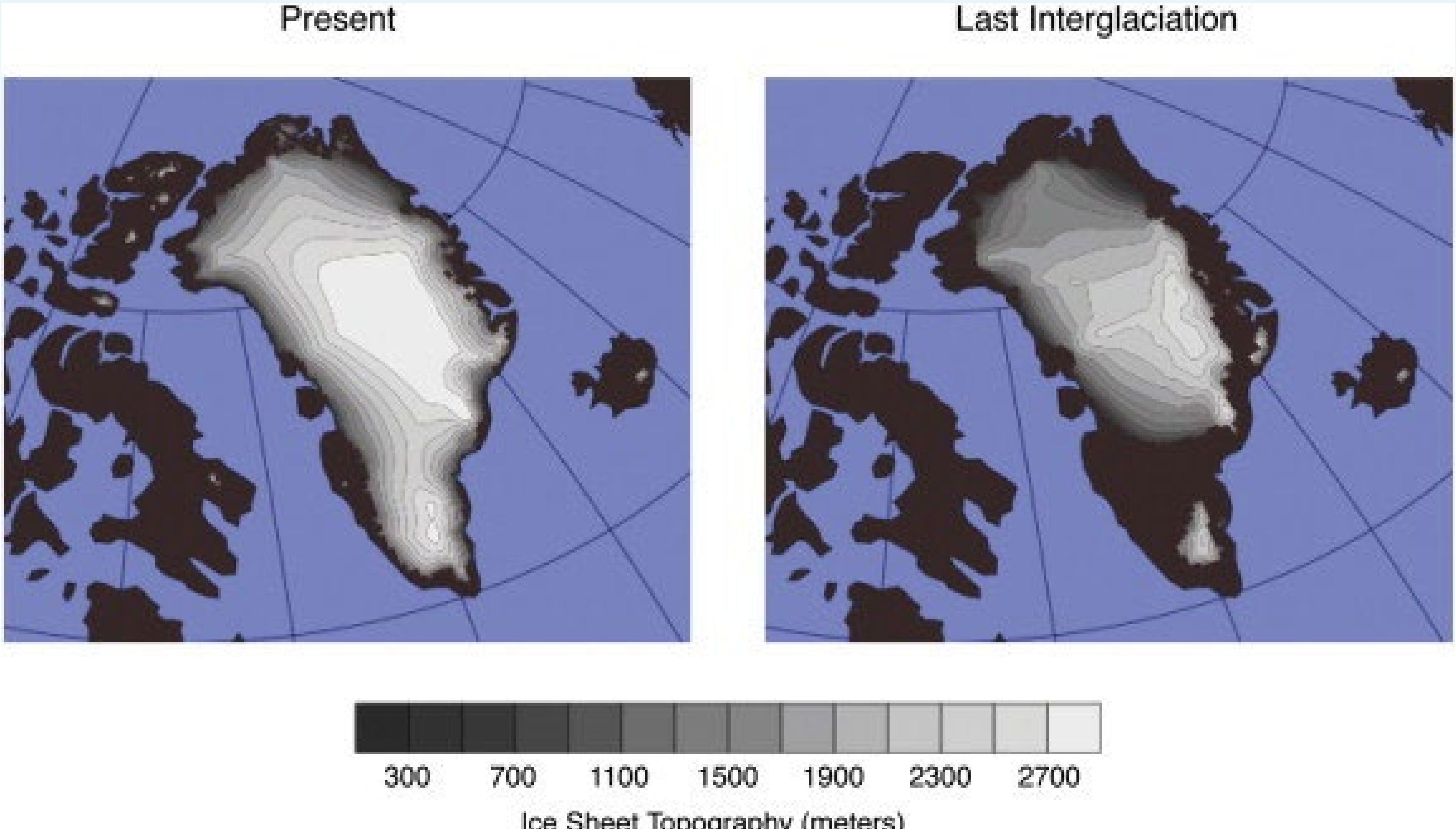
THE HISTORY OF LAST 150 KYR: FROM THE ISOTOPE RECORD

ISOTOPE RECORD

150Kyr
Glacial
130 -120 Kyr
Rapid deglaciation. IRDs are limited to very high latitudes (as today) because the Arctic ice sheet was absent (except for Greenland).
125-80Kyr
Presence of 23Kyr cycles.
63-21Kyr
Presence of 41Kyr cycles . LGM at ca.20Kyr.
17-10kyr
Rapid deglaciation.



THE HISTORY OF LAST 150 KYR: FROM THE MODELS



Otto-Bliesner et al. (2006)

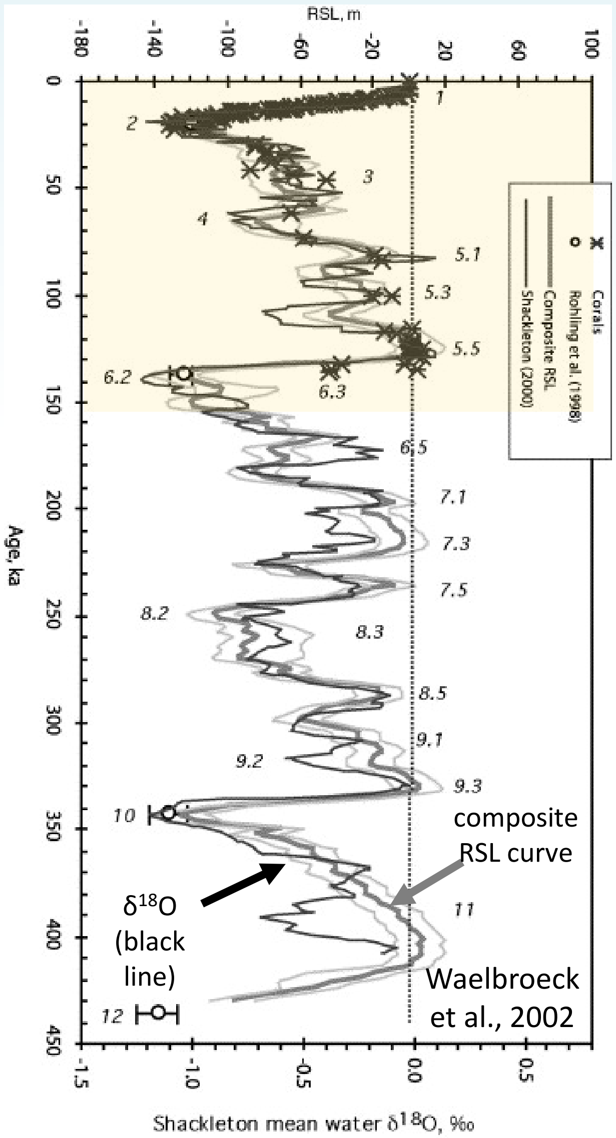
CONFIRMATION OF ICE VOLUME CHANGES: CORAL REEF AND SEA LEVEL -1

Today, corals prefer clear tropical waters near small islands over turbid waters near continents.

When sea levels rise or fall, corals move landward or seaward accordingly.

Over the past tens to hundreds of thousands of years, **global sea level changes** have been linked to **glaciations**, so fossil **coral colonies** help document ice volume variations.

CONFIRMATION OF ICE VOLUME CHANGES: CORAL REEF AND SEA LEVEL -1



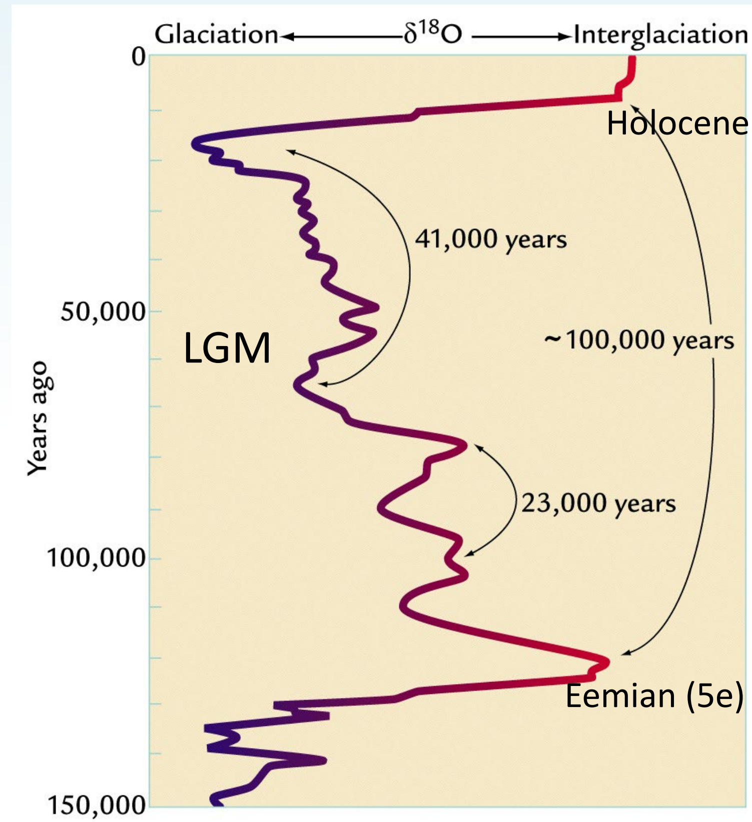


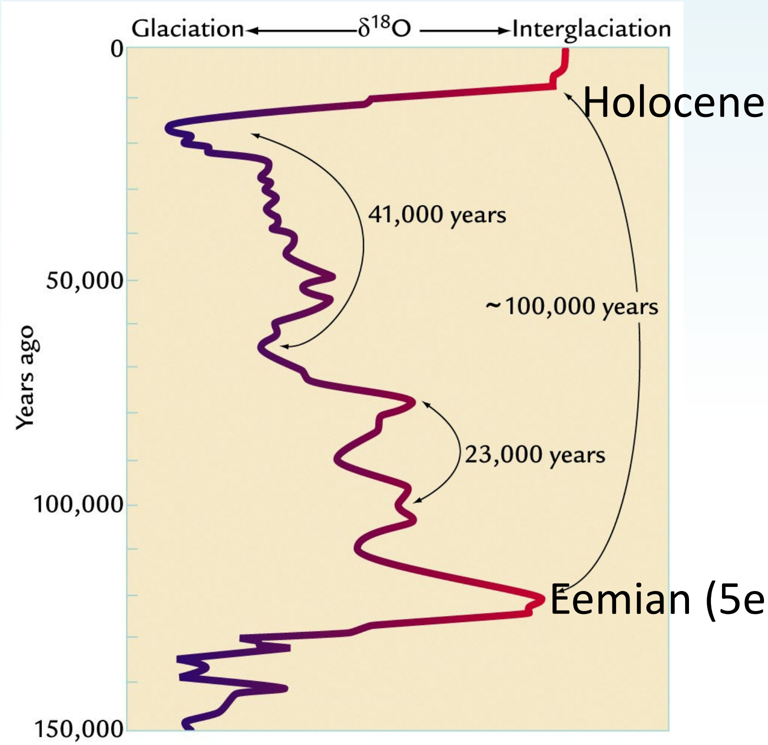
Fig. 4. Left axis: **Composite RSL curve (bold gray line)** and associated confidence interval (thin gray lines). Crosses: coral reef RSL data as in Fig. 1. Empty circles: RSL low stands estimated by Rohling et al. (1998). Right axis: variations in **mean ocean water $\delta^{18}O$ derived by Shackleton (2000) from atmospheric $\delta^{18}O$ (black line).**

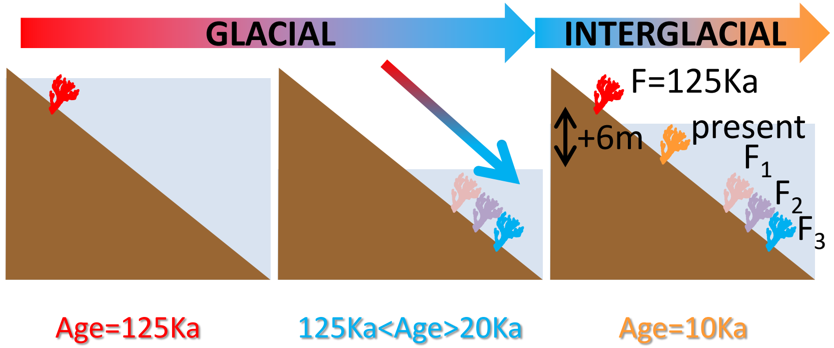
CONFIRMATION OF ICE VOLUME CHANGES: CORAL REEF AND SEA LEVEL -2

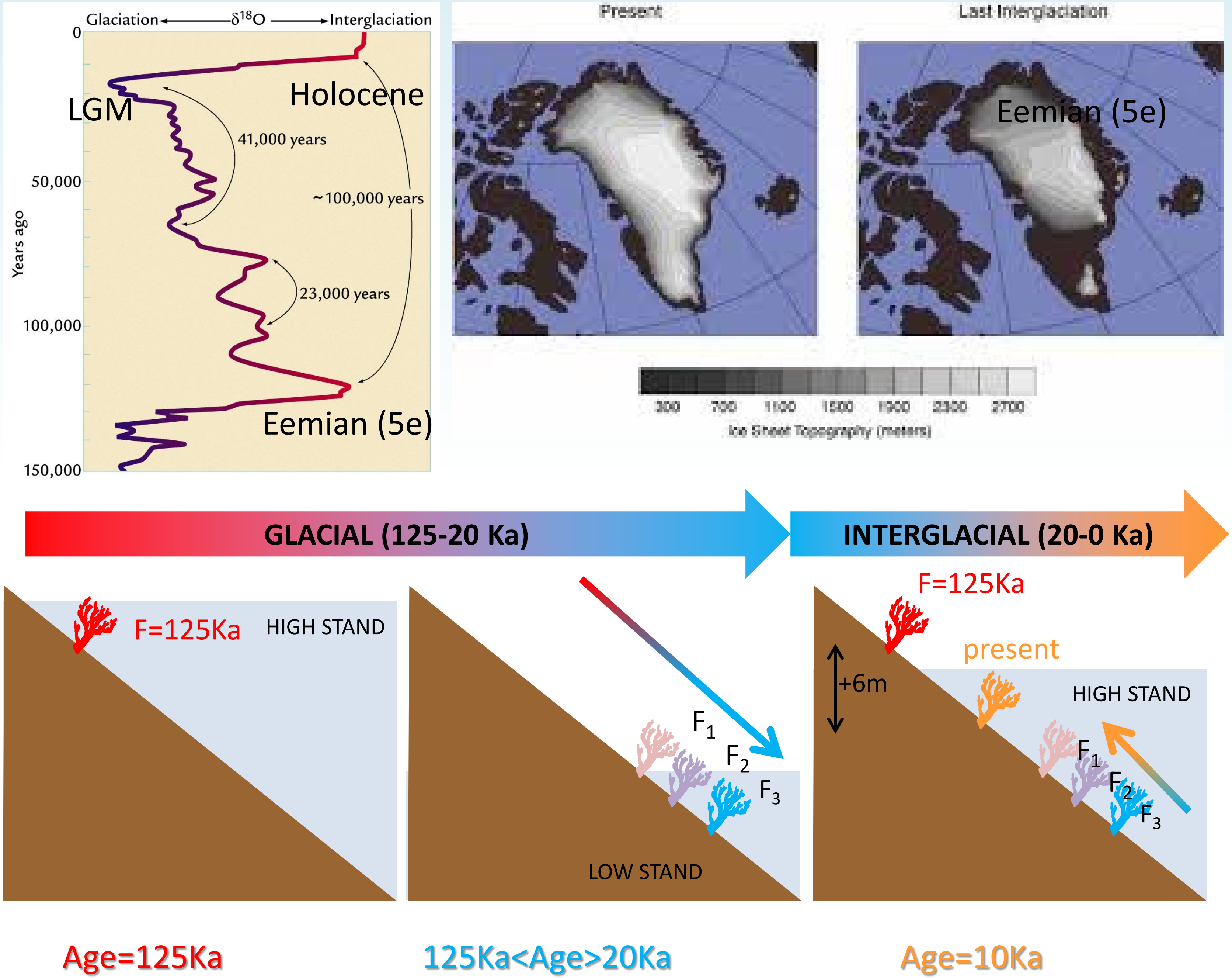
Fossil corals can be radiometrically dated ($^{234}U \rightarrow ^{230}Th$), linking sea level to $\delta^{18}O$ over the last 150 kyr.

Bermuda

A tectonically stable region with a fossil coral reef (125 ka; +6 m above sea level) indicates the only period in the last 150 kyr when sea levels were higher than today. Ice cap extent was similar, though slightly less than present (Fig. A). In stable areas, coral reefs from 130 to 20 ka are found submerged (Fig. B; F1, F2, F3).



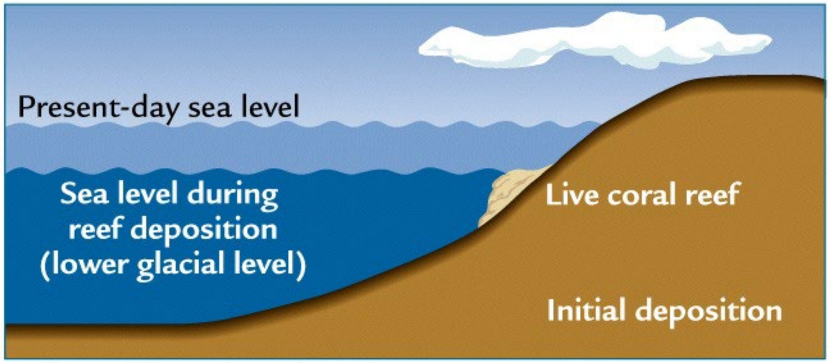



Glaciation ← $\delta^{18}O$ → Interglaciation
0
50,000
100,000
150,000
Years ago
LGM
Holocene
41,000 years
~100,000 years
23,000 years
Eemian (5e)
Present
Last Interglaciation
Eemian (5e)
300
700
1100
1500
1900
2300
2700
Ice Sheet Topography (meters)
GLACIAL (125-20 Ka)
INTERGLACIAL (20-0 Ka)
F=125Ka
HIGH STAND
F_1
F_2
F_3
LOW STAND
F=125Ka
present
+6m
HIGH STAND
F_1
F_2
F_3
Age=125Ka
125Ka<Age>20Ka
Age=10Ka

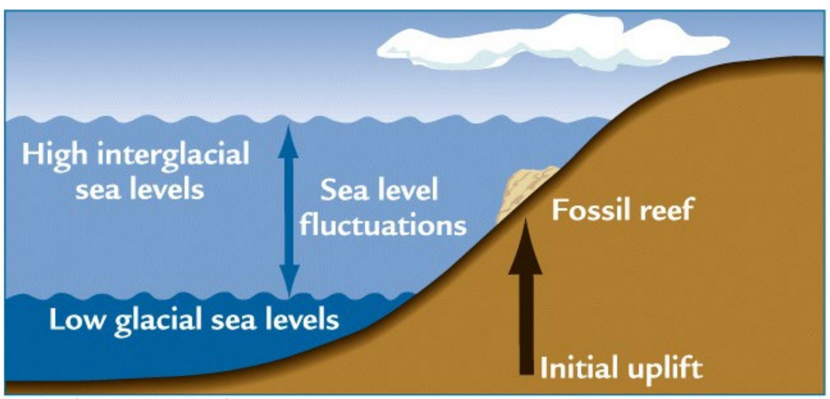
CONFIRMATION OF ICE VOLUME CHANGES: CORAL REEF AND SEA LEVEL -3

Barbados (Caribbean Sea) & New Guinea (Western Pacific)

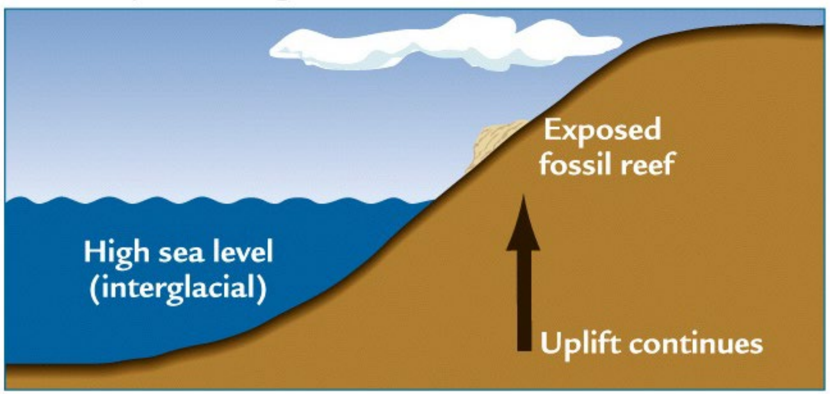
These tectonically unstable regions experience uplift, exposing coral reefs originally formed below current sea levels. Minimum $\delta^{18}O$ values occurred at 125, 104, and 82 kyr.



A Deposition of coral reef



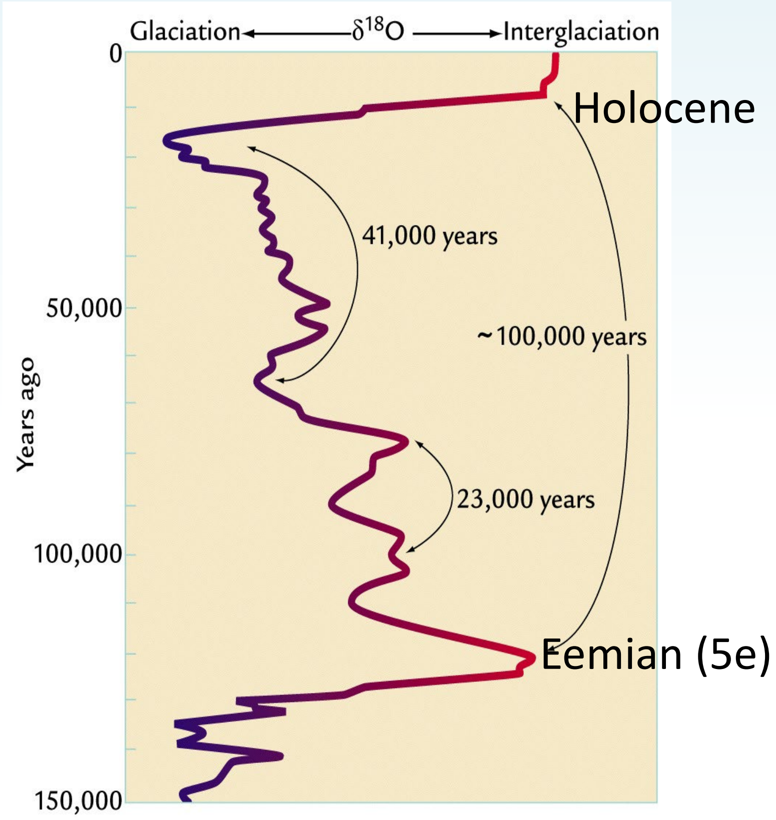
B Subsequent changes



C Present day

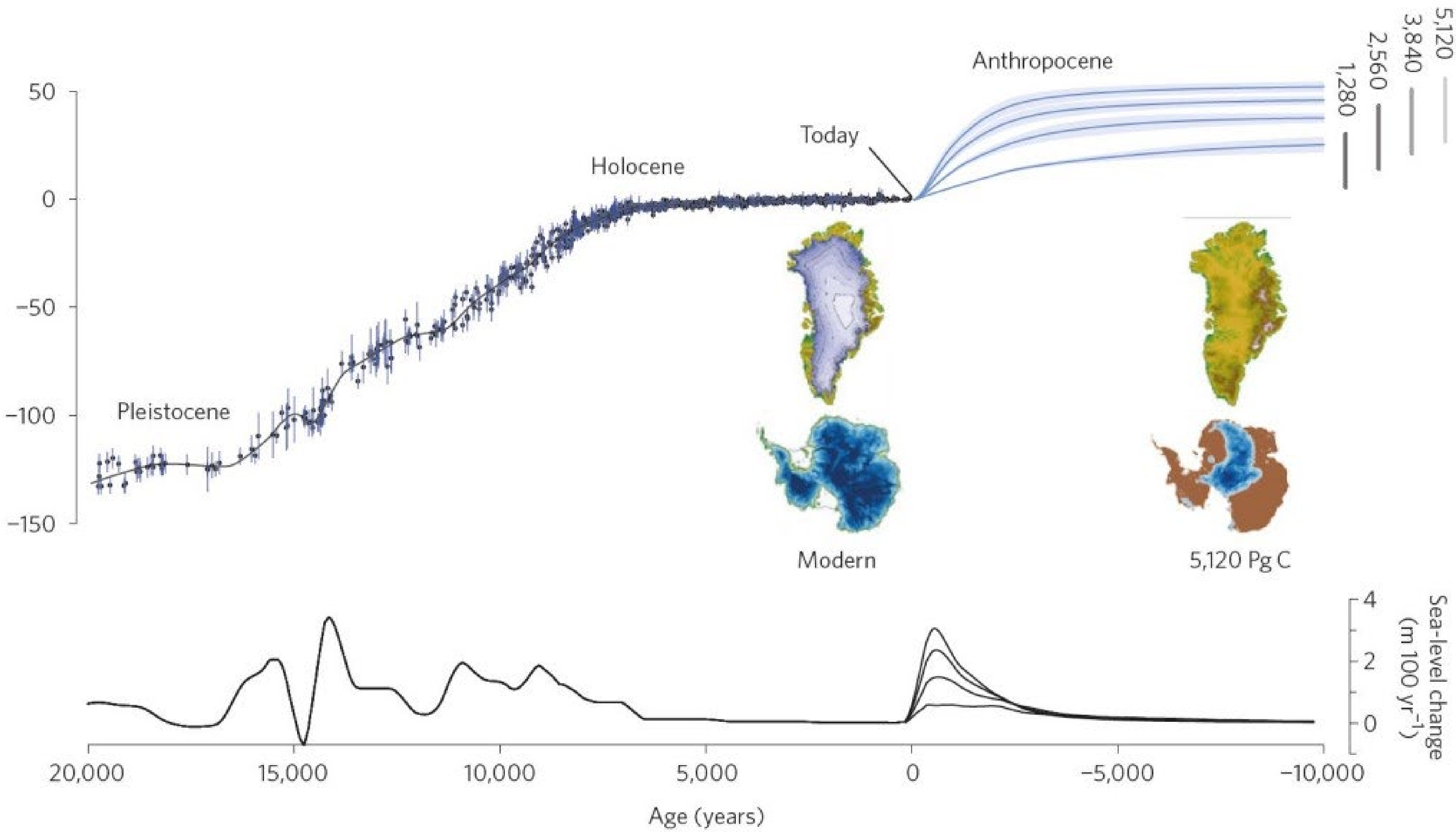
CONFIRMATION OF ICE VOLUME CHANGES: CORAL REEF AND SEA LEVEL -3

IODP Exp. 310 Mission Specific



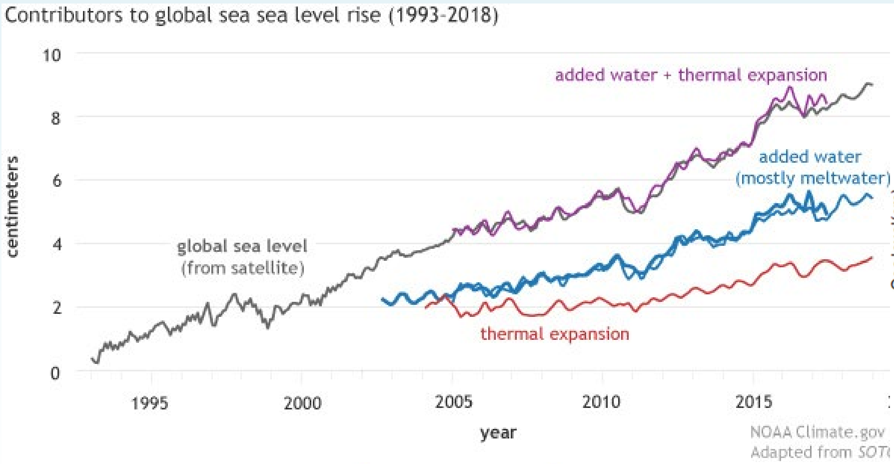
Tahiti (Slight Subsidence)
150 kyr ago, sea level was 110-125 m lower than today. The minimum level at 150 kyr (+6 m above current) serves as an anchor to adjust for tectonic effects.

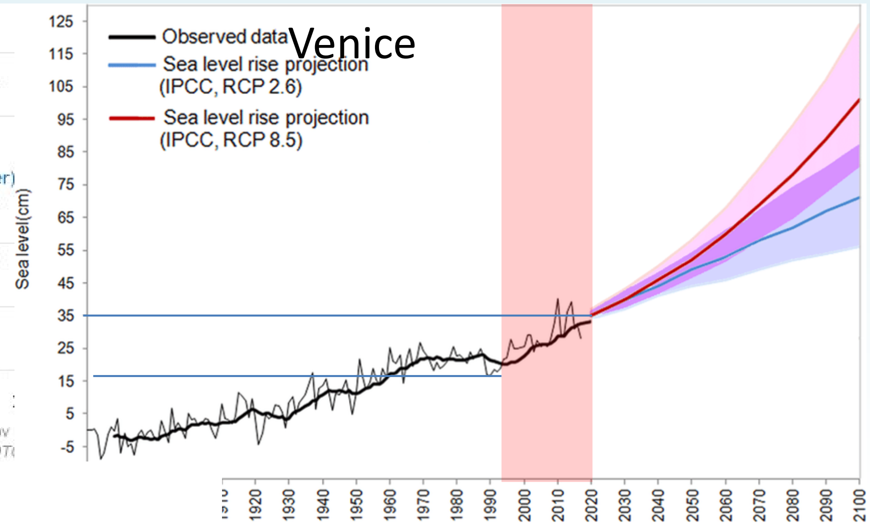
SEA-LEVEL RISE - ANTHROPOCENE

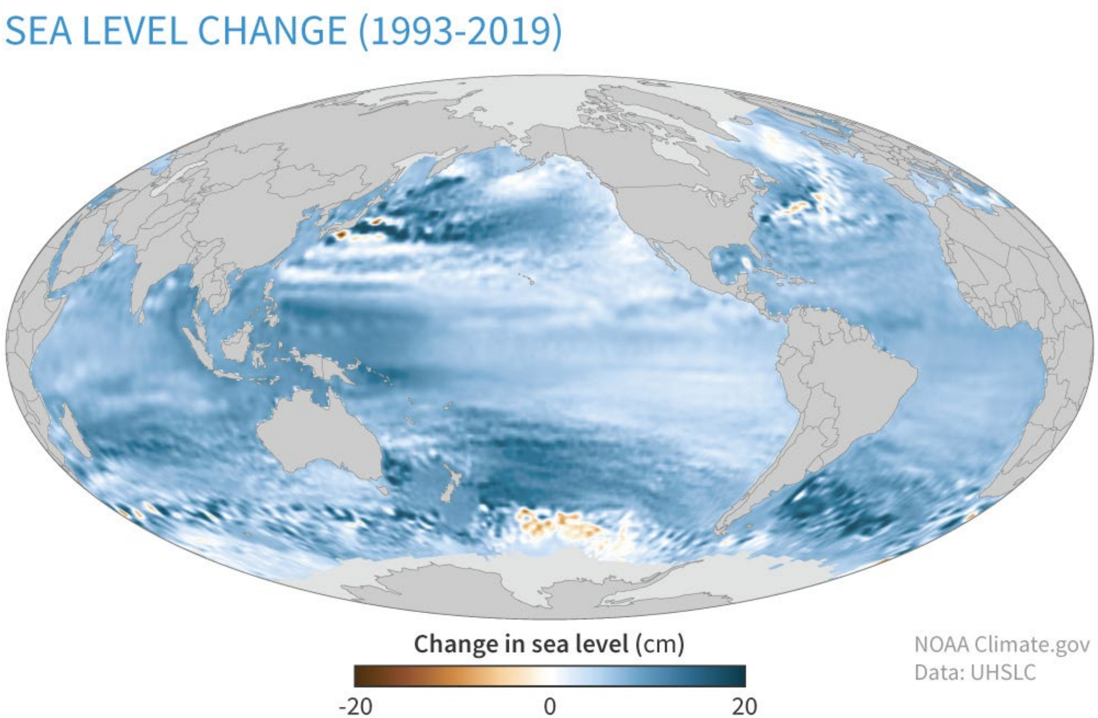


Clark et al. 2016

SEA-LEVEL RISE - VENICE







The global mean sea level rose by 3.6 mm per year from 2006–2015, 2.5 times the average rate of 1.4 mm per year during most of the 20th century.
Between 1993 and 2018, mean sea level increased across most of the world's oceans.